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AN ANALYSIS OF THE IMPACT ON U.S. INDUSTRY OF THE NIST/BOULDER SUPERCONDUCTIVITY PROGRAMS: AN INTERIM STUDY

Robert L. Peterson

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Electromagnetic Technology Division
Electronics and Electrical Engineering Laboratory
National Institute of Standards and Technology
Boulder, Colorado 80303-3328

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U.S. DEPARTMENT OF COMMERCE, Ronald H. Brown, Secretary
TECHNOLOGY ADMINISTRATION, Mary L. Good, Under Secretary for Technology
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY, Arati Prabhakar, Director

Contents

Abbreviations, Notation, Acknowledgment

Abbreviations

A/D	=	analog-to-digital
HTS	=	high-temperature superconductivity or high-temperature superconductor(s)
JJ	=	Josephson junction
LTS	=	low-temperature superconductivity or low-temperature superconductor(s)
MRI	=	magnetic resonance imaging
sc	=	superconductivity, superconductors, or superconducting
SMES	=	sc magnetic energy storage
SQUID	=	superconducting quantum interference device
SRM	=	standard reference material
SSC	=	Superconducting Super Collider
VAMAS	=	Versailles Project on Advanced Materials and Standards
YBCO	=	$YBa_2Cu_3O_{7-x}$, an HTS material

Notation

Within quotations, I sometimes use square brackets [ ]. Words within the square brackets substitute for company names (for example, [we] can replace a company name), or abbreviate or substitute for extended phrases without changing the meaning.

Acknowledgment

My thanks are extended to Gregory Tassey for answering many of my questions and for his many suggestions.

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Executive Summary

The National Institute of Standards and Technology (NIST) Boulder Laboratories has two Groups whose work includes superconductivity: the Superconductor and Magnetic Measurements Group, and the Cryoelectronic Metrology Group. They provide standards and measurement methods for superconductors, develop new superconductor devices, and conduct research in superconductivity.

This report is an interim study of the impact of the NIST/Boulder superconductivity programs on U.S. industry. Because the superconductor market is still small – the promising new technology of high-temperature superconductivity has not had time to significantly enter the marketplace – a detailed economic study of the NIST impact is not warranted. Nevertheless, it was felt useful to undertake a preliminary analysis of the impact of the NIST/Boulder programs. In this report, numerical estimates are made of the return on investment for areas which could be quantified. Anecdotal material and consideration of unquantified impacts are also included, and a survey of the U.S. superconductor industry is made.

We conducted in 1991 a survey of 40 U.S. companies or separate groups within companies involved in superconductivity. These companies include the major superconductor wire and magnet manufacturing companies and almost all companies within the superconducting electronics and high-temperature superconductivity fields that the NIST/Boulder superconductor groups have helped in recent years. Of the letters and questionnaires sent out, 33 responses were received, an 83% response [illegible]

Small, medium, and large companies are represented equally among the 40 surveyed. All respondents indicated benefit from the NIST/Boulder programs. No negative comments were made. The stated benefits included: improved productivity in manufacturing, assistance in design or understanding of a measurement process, improved ability to meet customer specifications, labor and other costs saved in research and development (R&D), new products developed, new technical information received, and contracts or grants secured. It is particularly noteworthy that 13 of the 33 respondents stated that their interactions with NIST had resulted in new R&D directions for their company.

Estimates of the economic benefit to *industry* (ratio of benefits to investment – NIST plus Other Agency – in the NIST/Boulder superconductivity programs) range from a factor of about 1 for the newer programs to at least 15 for the programs benefiting the wire and magnet manufacturers. If only NIST appropriations are considered, the ratio of benefits to investment is at least 50 for the wire and magnet industry. Apart from stated plans of three manufacturers of electronics instrumentation and already contracted work for the Superconducting Super Collider, these figures do not include expected *future* impact. They also do not include the impact on government or university programs, both of which are very substantial. The numerical estimates of return on investment also do not include benefits which could not be or were not quantified, for example the value of the new R&D directions for the 13 companies and the value of technical information which has not yet found its way into a new product.

In superconducting electronics, the greatest impact on U.S. industry of the NIST work has been from the Josephson junction voltage standards developed at NIST. In 1991, all major standards laboratories worldwide (about 30) had obtained the NIST designs and components for installing the voltage standards, and NIST was supplying about 20 voltage standard chips per year. Manufacturers of precision electronic instrumentation now recognize the utility of the Josephson voltage standards in manufacturing control and in assessing the performance of their world-leading instruments.

Every U.S. superconducting-wire manufacturer uses the measurement methods established by NIST for accurate determination of the critical parameters of the wire with which superconducting magnets are made. Tens of thousands of superconducting magnets are in use worldwide. The SSC project will require an additional 10 000 to 12 000 superconducting magnets. The growing magnetic resonance imaging (MRI) industry had estimated worldwide revenues exceeding $1.5 billion annually by 1992 and uses some 3000 superconducting magnets. One of the major manufacturing companies in MRI stated in its response, “Keep up the good work. We can’t really put a dollar figure on your help – it’s the basis of our business.”

An industry in high-temperature superconductivity is just emerging, with a few products now entering the marketplace. The true dollar impact of the NIST superconductor programs on the high-temperature superconductivity industry cannot be assessed at this early stage, but the potential market is enormous, and the NIST work is providing the foundations for the technology of high-temperature superconductivity. The Chief Technical Officer of one of the high-temperature superconductivity companies stated, “The recent work at Boulder ... is exactly the kind of generic work with an applied flavor that a national laboratory should be doing.”

I. Introduction

The worldwide superconductor (sc) industry is small compared to others such as semiconductors, microwaves, or optical communications. Nevertheless, the sc industry is expected to grow, particularly with the advent of high-temperature superconductivity (HTS), the increasing popularity of magnetic resonance imaging (MRI), and the increasing sophistication and application of sc electronics.

Market projections for superconductivity are notoriously difficult, as seen by comparison of the projections of two established forecasting companies. British-based World Business Publications Ltd. projected that by the year 2003, the total worldwide market for superconductors of all types would be $1.3 billion,[1] whereas the Nomura Research Institute of Japan projected the same market to be

[1]Referenced in Superconductor Week 3, 27 Feb 1989.

$43 billion for 2000, and $123 billion for 2010.[2] The worldwide market in 1988 for all sc products was estimated by World Business Publications at $172 million.

Because the sc market is yet small and much of it quite recent, a full economic analysis of the impact of the NIST/Boulder sc programs on the U.S. sc industry is not warranted. Nevertheless, a preliminary study was considered to be useful, and NIST in 1991 queried the principal U.S. sc manufacturing and research companies to estimate the impact of the NIST sc programs. The results of this study are reported in the following sections.

A brief history of superconductivity will help put the study into perspective. From the discovery in 1911 of zero electrical resistance, to the discovery in 1933 of magnetic flux expulsion, and until the late 1950s, there was little understanding of the nature of superconductivity, and little technological interest. Then in the period from 1957 to 1962, several discoveries led to renewed interest both scientifically and technologically. These discoveries included the development of a fundamental theory, the discovery of the Josephson effect, and the development of high-field superconducting magnets.

The sc magnets quickly found their way into laboratories, particle accelerators, fusion machines, and more recently into MRI systems; they have no serious competition from other magnets at the highest magnetic fields. The Josephson effect soon resulted in the development of magnetometers of unprecedented sensitivity, based on SQUIDs (Superconducting QUantum Interference Devices). Efforts to develop low-dissipation, high-speed electronics based on Josephson junctions followed soon after that. But the electronics industry was not accustomed to working below room temperature and did not rush to embrace the new capabilities provided by superconductors. The electronics industry was also quite aware that the capabilities of semiconductor technology had not yet been fully exploited.

Nevertheless, development of sc technology in the U.S. was underway from the mid 1960s. Superconducting magnet technology – with magnets made from low-temperature superconductor (LTS) wire – has since become a mature technology, with tens of thousands of sc magnets in use worldwide. The MRI industry uses more than 3000 sc magnets[3] and has estimated revenues for 1992 exceeding $1.5 billion annually. The Superconducting Super Collider (SSC) has been a major stimulus to LTS wire manufacturers. In the 1980s, LTS cable marketed for about $300/meter; currently the price is $50/meter, and if the SSC is completed the cost is expected to drop to about $3/meter.[4]

Markets for other uses of superconductivity have not developed this well. In the late 1960s, a company was formed to develop and market SQUID magnetometers, and since then a few other companies have entered that market. Although SQUID magnetometers are the world's most sensitive, they do become noisy at low frequencies where much biological interest lies; that and the relative expense due to the present necessity for liquid helium cooling has limited their economic

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[2]As quoted in Emerging Technologies in Electronics, 2nd ed., U.S. Department of Commerce, p. 31 (February 1990).

[3]Superconductor Industry **3**, p. 26, Fall 1990.

[4]Superconductor Week **6**, 3 August 1992.

impact. However, recent progress in the development of monolithic SQUID systems, microSQUID arrays, and magnetic shielding, some of it stimulated by progress in high-temperature superconductivity, suggests that a sizeable market may develop in biomagnetic applications (including real-time biomagnetism), nondestructive evaluation, education, and other areas.

In sc electronics, the Josephson junction (JJ) volt standards, for which NIST/Boulder is the pioneer, have found their way into all major national and industrial standards laboratories of the world. U.S. industry has realized that JJ volt standards can be used for assessing the performance of its highest-precision electronic instrumentation, which cannot be ascertained by conventional techniques, and has begun incorporating JJ volt standards in manufacturing control. But the rest of sc electronics has not fared as well in spite of its much superior speed and low heat generation. The necessity for liquid helium cryogenics with its required additional equipment and attendant costs is the principal reason. For several years, U.S. industry mounted a large effort to develop a sc computer, then backed off when it did not appear that such a computer would be economically competitive in the short term. Japan, however, forged ahead with ambitious plans in both sc electronics and large scale applications, with the Japanese government stimulating its sc industry with large financial incentives.

In spite of a small market, impressive accomplishments have been realized in sc electronics. Companies in Japan have developed 4-bit microprocessors with clock rates of 1 gigahertz. NIST/Boulder pioneered the development of sc analog-to-digital (A/D) converters; a U.S. company has further developed sc A/D converters and has begun to market instrumentation based on them, such as high performance digital oscilloscopes and transient digitizers.

The discovery of HTS at the end of 1986 once again injected new life into superconductivity. The technological applications of these superconductors are manifold (see Appendix A) and the potential markets are very large. U.S. industry was initially hesitant to mount a large effort to develop the new technology, realizing that many years would be required to develop practical HTS materials and devices. Recently, however, U.S. industrial interest has picked up, with many small companies being formed to exploit HTS technology and relying heavily on government support.

U.S. industry still considers most areas of superconductivity as high-risk technology. Given the economic environment of the past few years, few U.S. companies are willing to commit themselves to sc technology without help, except in a few specialized areas of electronics and in the more mature areas of sc wires and magnets. Even the sc wire and magnet area was significantly stimulated by the U.S. government through its support of particle accelerators at the national laboratories: the success of the sc magnets demonstrated their reliability and usefulness, and industry then entered the field of MRI largely without government assistance, although Medicare has helped to provide the customer base. The government-supported SSC has played a similar role by stimulating production of high-current-capacity LTS wire.

II. Statistical Data from a Survey of U.S. Companies

Basis of the Survey

In our effort to assess the impact of the NIST/Boulder sc programs on U.S. industry, we wrote letters to 39 companies and separate groups within companies. Responses were received from 31 of them. In addition, letters received from six groups before the study began are included in this analysis, giving a total of 33 responses out of 40 different groups, an 83% response rate. A listing of these companies and groups is given in Appendix B. A few additional companies with whom NIST/Boulder researchers have interacted were not queried because the NIST/Boulder people felt that no significant impact was made on them.

These 40 companies and groups include almost all those within the sc electronics and HTS fields that the NIST superconductor Groups have helped in recent years, and all the major sc wire and magnet manufacturing companies in the U.S. Questionnaires (a representative form is shown in Appendix C) developed in collaboration with Gregory Tassey, Senior Economist at NIST, were sent to the wire and magnet companies and to a few other sc companies with whom the NIST Groups had only a little direct contact. Personal letters of inquiry were sent to the rest.

Of considerable interest is the fact that no negative comments about the work of the NIST/Boulder sc programs were received. Those who have remarked on the merits of the programs are strongly supportive of the work.

A study of the responding companies shows a nearly uniform mix of company sizes (number of employees at a given location): about 10 to 12 each in the three categories (1) less than 50 employees, (2) from 50 to 500 employees, and (3) more than 500 employees. These proportions do not change much when we include the seven companies or groups which did not respond but which we know have benefited from the sc programs.

Six questions on the questionnaire asked for numerical estimates having to do with dollars saved and time saved. Other questions asked whether the company has marketed any new or improved products as a result of its interaction with NIST. The results of those questions are considered in the following subsection on Return on Investment.

Several other questions on the questionnaire, and comments in the letters received, have provided information valuable to the superconductor Groups but do not lend themselves readily to quantification in terms of dollars or time saved. These responses include:

- Twenty-six (79%) of the thirty-three responding companies indicated that they had benefited from *personal* contacts with NIST personnel.
- Twenty-five (76%) of the thirty-three respondents stated or implied that they had a better understanding of their existing or anticipated company product or process as a result of NIST programs.
- Thirteen (39%) said that they were better able to meet their customer specifications.
- Thirteen (39%) said that their interaction with NIST resulted in new R&D directions for their company.
- Interestingly, seven (21%) companies stated that they had been enabled to apply for or secure a contract or grant as a result of their interaction with NIST.
- Five (15%) said that the NIST sc programs had been essential for their marketing or contract work (traceability requirements or measurement assurance).
- Four (12%) respondents said that their companies anticipate developing new products as a result of the NIST interaction.
- Two have given prominent display to NIST assistance in their advertising and product promotion.

These types of impacts have not been included in our attempt to estimate the dollar value of the return on investment. Neither have we attempted to estimate the monetary value of the impact of hundreds of publications and talks, many of them invited. Members of both Groups frequently serve on advisory committees, organize and chair conferences, symposia, and workshops, and edit conference proceedings. The impacts of these activities likewise are not included in our monetary estimate of return on investment.

Return on Investment

In this section we estimate total dollars and labor saved and new revenue generated, as deduced from the answers to questions posed in different categories. Most respondents chose not to supply detailed information in these areas, probably because in most cases these items are very difficult to quantify, and also likely because they did not wish to reveal their success or lack of it. Our estimates based on extrapolations thus carry significant uncertainties.

Only a portion of increased revenue is increased profit, because of the cost of production. Companies seldom reveal their profit margins. Since the increased profits from sales are typically larger than the savings in productivity or shortened R&D time resulting from NIST assistance, it would be unrealistic to ignore the increased revenue as a benefit on the grounds that we do not know what profit factors to use. In order to be able to add increased revenue to cost savings, we assume for the purposes of this report that *average* profit margins are 100%, which we think is conservative, and take one-half of reported increased revenue as the associated benefit, which we label *net revenue* in the following.

We have also been sensitive to the possibility of inadvertently counting a single benefit twice, as could happen if, for example, increased net profits were reported by the company both as increased revenue and as cost savings from improvements in productivity or design. We have analyzed each of the responses with this in mind and have concluded that in each case where both increased revenues and cost savings were indicated, the two were indeed separate benefits. In Appendix D we expand on this topic and the topic of the preceding paragraph.

On the NIST investment side, we have converted the dollars spent in each year to 1991 constant dollars, using published inflation indices.[5] In the responses indicating benefits, we have assumed that dollar figures given are recent values, that is, 1991 dollars. Since this may not always be the case, this assumption tends to understate the dollar value of benefits.

We divide the impact into three categories: (1) LTS wire and magnet manufacturing and associated R&D; (2) LTS electronics manufacturing and associated R&D; and (3) HTS materials and electronics, of which all contacts are R&D companies, though some have recently started to offer HTS products.

LTS Wire and Magnets

We have identified 34 U.S. companies engaged in the manufacture of, or research on, LTS wire or sc magnets. Of these, we chose to query 14 – those with whom NIST has had direct interaction. Two of those not queried are very large companies that have been awarded contracts to make the more than 10 000 magnets for the SSC project and thus cannot claim impact from NIST as yet, although projected benefit is substantial (see below). Eleven responses from the fourteen queries

[5] Statistical Abstract of the United States: 1992 (112th edition), pp. 468, 469, 1992 (U.S. Bureau of the Census, Washington, DC).

were received. One of these responding companies is involved *only* in R&D, although all engage in R&D to some extent.

R&D: Shortened Time and Cost Avoidance

Only three of the eleven respondents were willing or able to state the amount of dollars and time saved on R&D because of NIST assistance, though six indicated that their R&D time had been shortened. One company stated that a minimum of $500 000 ($500K) of resources had been saved (which we interpret to include labor, equipment, and materials), and the other two each gave a figure of $100K. The responses indicate that these are total, not yearly, savings. The average of these three is $233K. Extrapolation of this figure to the other companies is uncertain; some of the companies probably saved little or nothing in R&D and others may have saved (or will save in the SSC project within the next decade) more than the largest of these. If we assume that the average for all 34 companies is the same as for the three, we would infer that NIST has saved these companies $7.9 million in shortened R&D time and cost avoidance in equipment and other purchases because of NIST assistance in generic design and development. If we extrapolate to only the six respondents who specifically mentioned shortened R&D time, the savings from the NIST program becomes $1.4 million. If we assume, conservatively, that the savings are to be amortized over 10 years, we obtain $0.8 million (or $0.1 million) per year.

Savings from Improvements in Productivity in Manufacturing

Just one of the wire and magnet companies put a dollar value on its improved productivity of manufacturing (because of better testing capability, better process design or control, etc.), giving a figure of $250K per year saved, plus six work-months of labor per year. We are confident that productivity of manufacturing was improved for at least most of the 33 manufacturing companies (34 less the one known to conduct only research) because of their reliance, directly or indirectly, on NIST-developed methods of testing or measuring wire and cable characteristics. We see little reason to think that the figures quoted by the one company could be grossly different from the rest. Multiplying the $250K and 6 work-months by 33 gives $8.25 million per year and 16.5 work-years per year saved in improved productivity of manufacturing resulting from the NIST program. The accepted 1991 labor cost of $120K per year per employee gives $2.0 million yearly saving in labor, which, added to the $8.25 million yearly saving from improvements in manufacturing, gives $10.2 million per year for this category.

Increased Revenue

None of the 10 respondents from the sc wire- and magnet-manufacturing companies say that they have been able to market new products, and we accept that as accurate. One indicated increased revenue from improvement of existing products, without giving a dollar value; another said he could not place a dollar value on the NIST help, but that it is the basis of his company's business. NIST-based measurement and specification of wire characteristics is in fact an improvement of existing products and provides the basis for improved competition from non-U.S. companies. The NIST program in sc wire and cable characterization has had an indirect role in the award to U.S. manufacturers to build the more than 10 000 SSC sc magnets. The average value of each of these magnets to the companies exceeds $100K, so the new revenue will exceed $1 billion in 1991 dollars. Spread over the five years estimated for completion, the new revenue would exceed $200 million per year. This is of course a one-time event, but it must also be remembered that tens of thousands of sc magnets have already been built in about the last 20 years, of which about 10 000 can be ascribed to U.S. manufacturers. The revenue from these sc magnets would be of the order of $1 billion in 1991 dollars, about $50 million per year, not counting the revenue from the systems of which the magnets are a part. Thus the average sc magnet revenue to U.S. manufacturers over a period of 25 years would be of the order of $80 million per year. This is consistent with the $172 million worldwide market for all sc products in 1988 given by World Business Publications[6] ($196 million 1991 dollars).

The *increase* in profits which can be attributed to the NIST program in sc wire and cable characterization is at best an estimate. For the company which stated that the NIST work was the basis of its business (and the other companies should be similar), we would be tempted to use a large fraction of profits as net revenue due to NIST. To choose the side of caution, we use 5% of the estimated $80 million revenue ($4 million per year) as a conservative figure for the benefit.

Economic Benefits

We add these three estimated yearly benefits:

<u>Savings from improved productivity in manufacturing</u>:	$10.2 million
<u>R&D savings</u>:	$0.8 (or $0.1) million
<u>Increased net revenue</u>:	$4.0 million

The total for the three categories is about $15.0 million (or $14.3 million) in benefits per year. Given the uncertainties of our estimates, we conclude that the actual value of the saving to the U.S. sc wire and magnet industry for those areas which we have considered quantifiable is probably not less than about $13 to $15 million per year and may be well above that figure.

These numbers are to be compared with NIST internal appropriations and Other Agency investments in the NIST superconductivity programs affecting the sc wire and magnet industry. The total investment over the past 10 years is $7.5 million in constant dollars (1991), or $0.75 million per year. The NIST internal appropriations alone averaged $0.26 million (1991) per year. On the benefits side, we have used estimated 1991 values for labor costs and assume that the dollar estimates given in the responses are recent (that is, 1991) dollar values. The latter assumption places estimated benefits on the conservative side.

Thus, the rate of return on investment in this area appears to be at least 15 (13/0.75 = 17) times the total investment, or at least 50 (13/0.26) for NIST investment, for the categories listed above. They do not take into account the unquantified savings related to the bulleted items on pages 4 and 5, the substantial NIST influence in standards committees, workshops, conferences, and round-robin measurements, nor the unquantifiable impact from the approximately 110 separate journal and book publications in the past 10 years. The actual rate of return on investment, or economic benefit, to U.S. industry will thus be considerably greater than our minimum estimates of 15 times total investment, or 50 times NIST investment.

<u>LTS Electronics</u>

We define LTS electronics for present purposes as including, in addition to highest-speed electronics made from LTS materials and Josephson junctions, other devices such as LTS SQUIDs, JJ voltage standards, sc frequency mixers, two-dimensional JJ arrays which may develop as infrared sources, and bolometers or infrared detectors made from LTS materials. Each of these areas is still

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[6]See Reference 1.

in the R&D phase, though LTS SQUIDs and JJ voltage arrays now have some commercial applications.

Thirteen groups have been identified by NIST as receiving direct help in LTS electronics, and replies were received from all of them. Of these, seven are manufacturers that conduct related R&D, one is principally a manufacturing company doing little or no R&D, and five are principally R&D groups within companies.

R&D: Shortened Time and Cost Avoidance

Eleven of the thirteen respondents indicated that R&D time was shortened and R&D costs were saved because of the NIST work. Of the eleven, one gave nine months total time saved in R&D, and another stated "years." The one manufacturer doing little R&D, mentioned in the preceding paragraph, indicated no R&D savings, appropriately; however, this company has used NIST designs totally in its marketed product, which is sold worldwide; in effect NIST has done all this company's R&D. We have included no estimate of R&D savings for this company because we have included its increased revenue from new products, below.

Estimating the average of 9 months and "years" to be 1.5 years, and extrapolating with the usual caveats to the 11 groups indicating R&D time savings, we have a total R&D time shortening of 16.5 years. If we assume conservatively that just one person is involved in this time shortening, this is equivalent to a labor savings of $3.3 million total for the 11 groups, at $200K/work-year (note the difference from $120K/work-year used for manufacturing).

Two of the companies estimated dollars saved in avoidance of purchases for generic design and development; the average of these two is $29K. Five groups indicated cost avoidance but gave no dollar estimates, and the rest gave no answer. Extending the two-company average of $29K to the twelve companies known to conduct R&D in LTS electronics gives $0.35 million saved; extending to just the five companies gives $0.15 million saved. Adding these figures to the estimated amounts saved in labor, we estimate total R&D savings in LTS electronics to be in the range $3.5 to $3.7 million, or $0.35 to $0.37 million per year assuming amortization over 10 years.

Savings from Improvements in Productivity in Manufacturing

Of the eight manufacturing companies in this group, three indicated savings from improved productivity of manufacturing (better testing capability). Just one of these was specific, stating $12K yearly because of installed equipment (Josephson voltage array), which we understand to mean the net yearly saving after subtracting implementation costs amortized over the anticipated life of the system. This company stated, in addition, 0.3 work-years per year of labor saved in production after NIST showed them how to automate the system. The savings in productivity for this company are thus $120K $\times$ 0.3 + $12K = $48K per year. Extrapolating to the three companies that have installed NIST JJ voltage arrays and which indicated that they had experienced productivity savings, likely for the same reasons, gives $0.14 million/year. Extrapolating these numbers to the eight manufacturing companies gives $0.38 million/year saved.

Increased Revenue

One company indicated revenue of $300K to $400K per year from new products produced as a result of the interactions from NIST, and the others did not enter numbers. However, one of those acknowledged in its response that NIST enabled them to put a new product on the market and has publicized its reliance on NIST achievements (JJ volt standard) in helping establish product specifications. Two others receiving substantial NIST help and equipment are placing new products on the market. If we conservatively estimate about $200K per year in increased revenue for each of the three companies that have installed JJ array standards in their production facilities, we obtain an estimated total of about $1.0 million per year in increased revenue from new products, or $0.5 million per year net revenue. None of the companies indicated increased revenue from improvement of existing products, which omission we question but accept for this report.

Economic Benefits

We add these three estimated yearly benefits:

Savings from improved productivity in manufacturing:	$0.38 (or $0.14) million
R&D savings:	$0.37 (or $0.35) million
Increased net revenue:	$0.5 million

The total for the three categories is about $1.0 million to $1.2 million per year of quantifiable benefits attributable to the NIST LTS electronics programs. These figures are no doubt conservative. They also do not include the unquantified impact of the 80 publications in this area in the past 10 years, the impact of many talks given at conferences, nor leadership and participation in committees and workshops. Four respondents stated that they were enabled to apply for or secure a contract or grant because of the NIST assistance. Translating this into return on investment has also not been attempted.

Internal appropriations and Other Agency investments in programs related to LTS electronics averaged $1.65 million per year (1991 constant dollars) over the 10 years prior to the survey. The NIST internal appropriations alone averaged $1.07 million (1991 dollars) per year. Since the benefit is estimated as $1.0 to $1.2 million (which omits the several unquantified elements mentioned above), the benefit to U.S. industry is about equal to the investment and is likely greater. A number of this order is expected, since sc electronics is still almost entirely in the R&D phase. If a sizeable market develops in LTS electronics, the return on investment will increase dramatically because the NIST work has already laid much of the foundation for industrial growth.

HTS Materials and Electronics

We have broken this area out separately because the industry it supports is in its embryonic stage, whereas NIST has received significant funding for it. A value for the monetary rate of return for the NIST HTS work is not yet meaningful. To have included it in the wire and magnet section or the LTS electronics section (the NIST HTS work is geared toward both) would have obscured the impacts of those efforts of NIST.

Twelve industrial groups working in HTS have received direct assistance from NIST and were queried. Nine responses were received. Of these, most are principally R&D companies or groups within the companies, although several hope soon to market new HTS products.

R&D: Shortened Time and Cost Avoidance

Seven of the nine respondents indicated that R&D time was shortened and R&D costs were saved because of the NIST work. Four estimated actual time saved in R&D, averaging four months saved and six work-months of labor saved in the four or five years they have worked in HTS. Again extrapolating with the usual caveats to the 12 (or 7) groups, we find an R&D time shortening of 48 (or 28) months, and labor saved totaling 6 (or 3.5) work-years. Multiplying the latter by $200K as above, we find $1.2 million (or $0.7 million) saved in R&D labor. Dollars saved from the months of shortened R&D time have not been included, since the responses show that a substantial portion of it includes the labor savings. Shortened R&D time would also affect other company costs, which likewise have not been included.

Six companies indicated dollar savings in avoidance of purchases for generic design and development, but just one company gave a value, estimating $200K. Extending this to the 12 groups is uncertain but not unreasonable and gives $2.4 million; applying it to only the 6 gives $1.2 million. Adding these to the estimated amounts saved in labor gives $3.6 million total saved in R&D when extrapolated to all 12 groups, or $1.9 million when extrapolating only to those actually indicating savings. These figures translate to $0.4 to $0.7 million per year, assuming that the benefits occured over the five year period since the discovery of HTS.

Savings from Improvements in Productivity in Manufacturing

None of the groups in HTS indicated savings from improved productivity of manufacturing and this is probably correct.

Increased Revenue

One of the nine indicated revenue from new products resulting from interactions with NIST. This company gave no dollar amount although the new units sell for $50K to $100K; we estimate that at least 10 units per year are sold, so the increased revenue is in the neighborhood of $1 million. These units do not use sc components; rather they are particularly useful in measuring the magnetization of HTS materials, so we have included them in this section. These units are the direct result of NIST assistance and design, and would likely not now be marketed without having had the benefit of NIST ideas and involvement. The other companies did not enter sales of new products, and none indicated increased revenue from existing products. Our personal knowledge of them indicates that this indeed is the case. Thus for total increased net revenue resulting from the NIST HTS programs, we estimate $0.5 million per year.

Economic Benefits

We add these estimated yearly benefits:

Savings from improved productivity in manufacturing:	$0.0 million
R&D savings:	$0.7 (or $0.4) million
Increased revenue:	$0.5 million

The total for the three categories is about $0.9 million to $1.2 million per year of quantifiable benefits attributable to the NIST HTS materials and electronics programs. These numbers do not include the unquantified values from impact of the 55 publications (to early 1991) and many talks given in this area, or the impact of leadership and participation in committees, workshops, and conferences. Four respondents stated that they were enabled to apply for or secure a contract or grant because of the NIST assistance. Translating this into return on investment has not been attempted.

Internal appropriations and Other Agency investments in programs related to HTS materials and electronics has averaged about $1.14 million (1991 constant dollars) per year since the inception of these programs. The NIST internal appropriations alone averaged $0.62 million (1991 dollars) per year. Comparing to the estimated $0.9 million to $1.2 million impact (which omits the several unquantified elements mentioned above), we see that the return by 1991 was already comparable to or greater than the rate of investment. The emerging HTS field is still almost entirely in the R&D phase. When the field matures and the expected large market develops in the next decade or so, the benefits from the NIST program will increase dramatically because of the foundational and metrological work of NIST in areas such as pioneering demonstration of "step-edge" Josephson junctions, careful characterization of HTS thin film properties, and early development of very-low-resistance contacts between normal metals and HTS materials, all of which are technologically vital.

III. Additional Analysis from the Survey and from Other Sources

Having made estimates of dollar impacts of the NIST sc programs on U.S. industry, we turn now to other, generally unquantified, impacts. Because the two NIST/Boulder groups working in sc play different roles within the sc community and provide different types of services, it is logical to separate them in what follows. We first describe the sc programs of these groups by objective and focus of impact, then follow with discussions of the impacts and benefits which were not given in the preceding Section.

Cryoelectronic Metrology Group

This Group's focus in superconductivity is to develop sc electronic measuring methods, devices, systems, and standards of superior accuracy, sensitivity, and speed to support new developments in technology; and to establish the technology for electronic devices which use HTS materials.

Impact – Comments from Respondents, with Discussion

Several U.S. companies have sent letters commending the NIST work on JJ voltage standards and thanking NIST for its assistance in getting voltage standards installed. One of the U.S. manufacturers of precision electronic instrumentation has used a picture of the NIST JJ voltage standard system on the front page of a publication promoting its products. A representative of this company states in a letter to NIST: "As the sophistication of instrumentation grows, the challenges in verification of performance seem to be pushing many of our classical standards to their limits or beyond. In this case, the Josephson array appears to be the only solution. The fact that the array has now reached the 10-volt level is a tremendous advantage in evaluation of our product's performance, and makes the array an attractive possibility for industrial standards labs such as ours. It is really impressive that you have made it possible for engineers of reasonable sophistication but without extensive physics knowledge or background to so easily make use of this state-of-the-art device."

Three other U.S. companies have considered developing and marketing their own JJ voltage standard systems, and to date (1992) one is actually doing this. It markets 10-volt JJ standards based on NIST designs; not only did the NIST work save them great expense in design and set-up, but, according to their own statements, they would not be in this area of manufacture were it not for the NIST sc program. Another company is collaborating with NIST to see whether less expensive components can be incorporated into the Josephson array system in order to drop the overall cost and thereby open up the market. Still another has used the NIST-designed voltage chip as a prototype in developing its own chip for potential marketing of a voltage standard. "[NIST] was most helpful in assisting [us] in the design and evaluation of the chips and identifying the short coming of our niobium technology. [We] benefited significantly from this work and will continue [our] collaboration with NIST on this project if needed."

We turn now to sc electronics more generally. LTS electronics has not yet developed a significant market because of the necessity for liquid helium cooling. Nevertheless, the NIST program has had substantial impact on several R&D groups in circuit design and fabrication and is one of the pioneers in this field. One of the facilities which requested NIST help in establishing measurement techniques for analyzing sc circuits and devices states: "The NIST assistance saved us years in attaining this capability." In the early 1980s, a large company shifted its sc programming into cryogenic electronics. "This transition was helped immeasurably by the interaction with the Cryoelectronics Group at NIST... [It] allowed [us] to quickly establish credibility in [sc] circuit fabrication which resulted in significant funding support from both internal and external sources." NIST has assisted them in developing a sc flux-counting A/D converter for use in infrared focal-plane array imaging systems. Their response letter states: "One measure of the significance of this achievement is the fact that it was reported at the 1990 Applied Superconductivity Conference as the only invited paper on digital electronics from a U.S. institution. As a result of this collaboration, and in direct competition with other contractors, [we were] awarded a follow-on contract to provide a real-time imaging demonstration with a superconductive A/D converter as a key component."

NIST was also one of the pioneers in SQUID technology. One company which markets SQUID magnetometers noted early NIST assistance in its development of SQUIDs. Another company asked for NIST assistance in acquiring SQUID expertise ". . . in order that we might improve our competitive position for a major space instrument which required a state-of-the-art dc SQUID as a key component in the sensor system. ... Our understanding of low-noise SQUID sensors that resulted from our collaboration with your group was one of the key reasons we were awarded a contract with the Department of the Navy in 1990."

The NIST work on sc infrared detection was sufficiently new in 1991 that only a few contacts had developed, and one had received NIST help. That company stated: "[We have] benefited through a better understanding of the physics of sc infrared detectors. This has allowed us to make more informed choices for the direction of our program."

Similarly, the HTS work at NIST is sufficiently recent that few demonstrated impacts are possible. One company has received direct NIST help in HTS technology, specifically in measuring the microwave surface resistance of thin-film YBCO. Its respondent stated: "With NIST support we were able to sustain a position within the HTS technology community and to respond to government solicitations. . . . Without your cooperation we would have had to establish in-house capabilities for transition temperature measurements and do research on etchants and etch rates on samples that we could not afford. . . Our cooperation allowed us to avoid duplicating work and to spend our resources on advancing the state-of-the-art."

Finally, a start-up HTS company stated, with reference to the NIST/Boulder work: "It is exactly the kind of generic work with an applied flavor that a national laboratory should be doing. Now if only we had a reliable junction technology! Perhaps you will do that next for us." Subsequent work at NIST has accomplished that.

Impact – Information from Other Sources

- The greatest impact of the Cryoelectronic Metrology Group has been from the Josephson junction voltage standards, which were developed in the Group. About 30 standards laboratories in U.S. companies and in other institutions, both U.S. and foreign, have obtained the NIST designs and components for installing the voltage standards. NIST in 1991 was supplying about 20 voltage standard chips per year.
- Although manufacturers of precision electronic instrumentation now recognize the utility of Josephson voltage standards in assessing the performance of their manufactured instruments and in manufacturing control, there are perhaps only a few dozen companies in the world making such instrumentation. Further, the total number of standards laboratories in the world is not a large number. The uses for JJ voltage standards mentioned here thus will never develop into a major *direct* economic market. Nevertheless the *indirect* benefits, which are not quantified in this study, of this transfer of sc technology are felt throughout the world through the widespread use of precision instruments and through the calibrations performed in standards laboratories.

Impact – Anticipated

- Demand for JJ voltage standard chips is increasing and requires increased efficiency of fabrication and longer junction life, which subjects NIST is actively pursuing. NIST is the only U.S. source of Josephson array voltage chips.
- The demonstrated performance of a single-electron-counting electrometer gives credibility to future metrological devices based on this technology. The expectation is that in a few years the single-electron devices will lead to a current standard in integrated circuit form.
- An improved microwave power standard is needed by standards labs in industry and government. The NIST results on the sc microwave power standard – sufficiently low loss to make a new power standard of 10 times better accuracy – have demonstrated a relatively low-risk path toward a significant improvement.
- The results of the Group on IR antennas – 52% efficiency at a mean wavelength of 19 micrometers, a new record – may change the approach to the design of IR detectors.
- Several U.S. companies are now marketing HTS products, including thin films and HTS-based electronic devices such as monolithic SQUIDs and microwave resonators and filters. Identifiable NIST impacts on an HTS electronics industry, particularly in HTS JJ fabrication expertise, should soon appear.
- The potential market for HTS electronics is very large because the modest cooling requirements of HTS permit significant entry into the enormous electronics market. Much projected *semiconductor* electronics will use the same cooling as already is used for HTS, and the linking of the two technologies is natural. The present limitations of HTS are subjects of vigorous work throughout the world, and many areas, such as reproducible Josephson junctions, are expected to see satisfactory resolution. HTS will become a great competitor to LTS in the next few years in many areas. LTS will hold its advantage for applications requiring the lowest possible noise and greatest sensitivity.

Superconductor and Magnetic Measurements Group

This Group's focus in superconductivity is to develop a basic understanding of LTS and HTS materials and measurements to enable standardization of measurement techniques; provide generic data, models, and measurement methods needed to support the design, construction, and operation of superconducting systems; and provide a common base for interaction among system designers/manufacturers and materials manufacturers.

Impact – Comments from Respondents, with Discussion

The LTS wire and magnet manufacturers uniformly commended NIST assistance in providing measurement techniques and the critical current Standard Reference Material (SRM). Of additional interest are their comments on the need for more measurements and help with non-sc materials as well as with sc materials. A large company referred to its need for the "ability to detect flaws in copper parts both cast and machined, primarily casting flaws and porosity, and niobium/titanium defects internal but too small to be detected by ultrasonic [methods]." They appreciated NIST's interest in real problems: "NIST technical personnel have been quite helpful over the years to offer solutions to real problems."

Another major manufacturer of sc wire and MRI magnets acknowledged many areas of NIST assistance, then picks up the theme of materials properties in addition to sc: "The investigation on stress and strain effects on superconductivity is very useful along with various standards on superconducting properties. The data of cryogenic properties of various materials is very handy." This company developed a list of problems which are barriers to its progress in sc: "1. Lack of standards for sc properties. 2. Lack of data of cryogenic properties of various materials. 3. Processing parameters. 4. Lack of instruments and techniques."

Still another producer of NbTi alloy rod and composite wire commented on development needs auxilliary to sc; after stating that the NIST programs in LTS measurement standards, SRMs, and characterization of materials is important to them, the respondent said that the unreliability of cryocoolers is a concern to them. Another company also echoed this need for good cryocoolers. The need for cryocooler development is a recurring theme in the sc literature.

A major manufacturer of MRI sc magnets states in its response that it finds all wire-related areas of the NIST sc programs of value to it, including the work on analysis of HTS materials, and that its productivity of manufacturing has been improved because of the NIST work. They state: "Keep up the good work. We can't really put a dollar figure on your help – it's the basis of our business."

A major maker of LTS wire acknowledged the crucial role of the NIST sc programs in standards and measurement. "I can safely say that our research and development programs. . . have been greatly assisted by the programs at NIST and that without your help we would not have achieved so much so soon."

A division of a large company designs and manufactures sc magnets, and will have a large role in producing sc magnets for the SSC. They acknowledge the vital role to them of all the NIST sc wire-related programs. A maker of niobium products stated that NIST's programs in LTS measurement standards, SRMs), characterization of materials, and development of LTS SQUIDs and circuits are all valuable to it. They wish that NIST could spend more time helping them *qualify* their materials. Another company which manufactures sc wire, tape, and cable states that its products are more reliable as a result of the NIST work and that the LTS measurements, standards, and characterization are of greatest value to them.

A large company which has collaborated with NIST in a program to understand ac loss in multifilamentary sc strand stated that it would be helpful for NIST to be a clearinghouse for the measurement and distribution of samples of wire and strand made by different companies.

We turn now to the responding companies concerned with HTS development. A small company manufacturing HTS wire and coils commended the NIST critical current SRM and stated that the NIST/Boulder analysis of HTS materials has been of value to them. One fairly small company, which is nevertheless a major manufacturer of LTS magnets, stated that the area of most interest to them among the NIST sc programs are those in HTS, and identify this help with new directions for the company. Five of the largest LTS wire and magnet manufacturers also stated that the NIST HTS work has been of use to them. These comments show that the wire and magnet makers are becoming serious about implementing HTS materials into their systems. Said one, "NIST has contributed much to our research and development of Nb_3Sn and HTS materials and their implementation into applications."

A division of a large company which is attempting an entry into the HTS business thanked NIST for its help in getting them underway in understanding microwave properties of HTS structures. A small group of another large company which conducts R&D on electronic materials acknowledges help from NIST in measuring the critical parameters of HTS thin films, and would like NIST to provide SRMs for HTS tapes. Another small group in a large company similarly has benefited by NIST collaboration: "Being able to work hands-on with the group at NIST has saved at least six work-months in getting up to speed in understanding the physics and measurement techniques of HTS."

NIST helped a manufacturer of electronic instrumentation to develop a system for measuring the magnetization of sc films as well as other materials. They praise the NIST assistance in their response and also give NIST very prominent mention in their advertising. A mass mailing (summer 1991) of a large glossy brochure which promotes their products includes a recognition of the assistance of NIST in the design of one of their instruments. The same brochure contains an insert containing NIST's *Units for Magnetic Properties*.

Finally, a research center of a large company, having collaborated with the Group in developing electrical contacts between HTS films and silicon, states that it plans to enter the hybrid technology of superconductor/semiconductor electronics, for which it feels a market will open. The company's plans in this field have been substantially advanced because of NIST assistance, according to their response.

Impact – Information from Other Sources

- The greatest impact of the Group lies in the measurement methods it has developed for the critical parameters of superconducting wire. Every U.S. sc wire manufacturer uses these measurement methods and thus all U.S.-made sc magnets are affected by this program. The Group's standards work is used in all planning and conductor procurement for fusion energy, high energy physics, and magnets for medical imaging.
- DoE requested NIST participation in its program on HTS standards for large scale applications such as sc magnetic energy storage (SMES) systems, power transmission, motors, shielding, and sc bearings.

- The existence of the fundamental limitation of strain on the performance of large electromagnets was discovered at NIST. Many people come to the Group from around the world for consultation on the effects of strain on superconductors of all sorts.
- In response to industry and DoE requests, special efforts have been made to assist the development of conductor for the SSC and fusion energy experiments such as ITER (the International Thermonuclear Experimental Reactor). The results of this work strongly influence the choice of conductor for new superconducting magnet systems.
- The ac loss behavior of the complex composite superconductors used in SSC is a limiting factor in their application. The Group's work has been instrumental in providing the information needed to determine the effect of cable losses on the overall magnet system. The design specifications for the conductors in the SSC have been influenced by NIST work.
- Examples of NIST assistance with measurement problems include a SQUID manufacturing company which received assistance in evaluating its newly designed SQUID susceptometer, and a large company which receives regular assistance in its development of HTS tape.
- The Group has been involved in HTS cooperative programs with major organizations, many of which have been willing to entrust valuable specimens of new superconducting materials to NIST for measurement because of the Group's experience and reputation in the field.
- A wall chart developed at NIST showing the low-temperature properties of copper and its dilute alloys, used in sc wire, hangs in nearly every cryogenics laboratory in the world.

Impact – Anticipated

- The potential market for HTS wire is very large because the modest cooling requirements of HTS permit significant entry into the superconductor magnet market. Development of flexible, long HTS wire for magnets is the subject of vigorous work throughout the world. When this is achieved, as is soon expected, it will greatly affect the sc magnet market. Some LTS and HTS technologies will merge; for example, the use of HTS wire at 20 K (that is, out of the conventional HTS temperature regime) in magnets may yield larger magnetic fields than possible with LTS materials.

Impact by Interlaboratory Comparisons (Round Robins) and SRMs

- Active and passive critical current simulators developed in the Group to test critical current measurement systems are used in round robin tests.
- Members of the Group organized the U.S. participation in superconductor critical current and ac loss for the VAMAS round robins.
- SRM-1457 is the only SRM in the world for the measurement of superconducting critical current. These SRMs are lengths of well characterized NbTi wire. Since 1984, when SRM-1457 was first made available, about 160 units have been sold, about 100 of them to Japan.
- Two interlaboratory comparisons of critical current are ongoing, one by VAMAS and one by the SSC Laboratory Quality Assurance program. The latter comparison is intended for certifying testing laboratories for SSC wire procurement.

IV. Summary and Conclusions

The study has shown that the sc effort at NIST/Boulder has significantly influenced all areas of superconductivity, from manufacture of sc wire, design and testing of magnets, design and manufacture of sc electronic devices and instrumentation, development and standardization of measurement and testing procedures, and characterization of LTS and HTS materials, to the basic science of superconductors. Every U.S. company which has developmental interest in LTS electronics has interacted with NIST/Boulder and almost all have received a measurable impact. The same is true of the companies interested in HTS, except for a few start-up companies for which interaction has not had time to develop. Not all U.S. sc magnet manufacturers have had direct interaction with NIST but have nevertheless benefited from the measurement methods and standards developed at NIST.

Estimates of the economic benefit to U.S. industry (rate of return on NIST investment) have been made in the categories of LTS wire and magnets, LTS electronics, and HTS materials and electronics. Only a portion of the impact could be quantified. The return (benefit/investment) in the wire and magnet category was estimated to be greater than a factor of 15 when NIST plus Other Agency funding is used, or greater than a factor of 50 when NIST appropriations alone are used. The return for the other two categories was estimated to be about 1, which was expected because the LTS electronics and HTS industries are still very small. These numbers do not include quantifiable impact on other institutions such as Government agencies and universities. Comments received from the U.S. industry respondents to the survey were uniformly favorable to the work of the NIST/Boulder sc programs, and were summarized in the preceding Section along with several other categories of impact.

Although the overall sc industry in the U.S. is small when compared to well-established and mature industries, the market is growing in several directions. A few of those mentioned in this report and some others are summarized here (numbers appropriate to mid-1992). Appendix A contains further detail and documentation.

- MRI is growing rapidly as a diagnostic tool and is poised for an even greater rate of growth if new scanning techniques, orders of magnitude faster than present, are implemented. New magnetic shielding for MRI systems is under development and will permit use of higher fields. When HTS magnets become a reality, MRI costs will be reduced to where many smaller facilities will be able to purchase systems.
- A U.S. company has delivered two SMES units for short term power backup. EPRI asserts that small SMES units will be the biggest use of sc after MRI.
- SQUID magnetometer systems are demonstrating their flexibility, and nondestructive evaluation of structures is a recent area of application, extending it beyond its traditional emphasis in biomedicine. The recent successful development of HTS SQUIDs promises greatly reduced cost of magnetometer systems when fully implemented.
- In addition to having been implemented in all major standards laboratories of the world, Josephson volt standards are now being installed in manufacturing facilities of electronic instrumentation. Current work to develop less expensive Josephson volt standard systems could bring wider industrial use of them.
- Potential HTS applications are manifold; we mention three here: (1) Several companies and research groups are working very hard to manufacture long-length HTS wire capable of carrying enough current to be of use in sc magnets and power transmission; short lengths which have the requisite properties have been fabricated. (2) Several groups have now successfully fabricated reproducible Josephson junctions in HTS materials, and there is currently much work in developing useful integrated circuits of HTS materials, or which incorporate HTS materials. (3) Microwave surface resistance is very small in HTS materials, and several companies are actively pursuing microwave devices which take advantage of this.

In addition to the HTS opportunities mentioned above and in Appendix A, there is another realm of application of HTS materials, often overlooked. This is the use of the HTS materials at liquid helium temperatures (4 K) or at liquid hydrogen temperatures (20 K). Many HTS materials have been shown to have superior properties - particularly higher critical magnetic fields - than the conventional LTS conductors at those temperatures. Critical currents in the HTS materials are now nearly competitive with the LTS materials.

Developmental work in LTS electronics is proceeding, with new emphasis on integrated circuits based on single flux quantum logic, which should give yet greater speed and reliability to sc electronics applications. The NIST-developed sc infrared detectors and antenna systems hold promise for industrial applications in microwaves.

The continuing development of small and inexpensive cryocoolers gives reason for optimism for more widespread use of LTS electronics. These cryocoolers do not use liquid helium and its attendant apparatus, and allow development of smaller, more flexible, and perhaps less expensive LTS electronics systems. Areas such as cryogenic cooling must be developed to interest main stream engineering companies. When reliable and inexpensive cryocoolers become available, a sizeable market will open up for sc applications already developed, and perhaps new ones.

The study has also shown that members of the staff are frequently asked by industry, university, or government personnel to make measurements or characterizations for them. Often the reason is that the requestors do not have the equipment to make the measurement. The service thus saves them the cost of purchasing the equipment. When the NIST assistance permits the company to avoid purchasing equipment, a large dollar figure saving can be realized. In other cases, the requestors do not have the expertise to make the measurements. The saving to them in this case is that personnel do not have to be trained or perhaps hired. Quite often, NIST personnel provide training to industry personnel. In some cases, the company would not have been able to provide any commercial sc product at all had it not been for NIST assistance.

Appendix A. Areas of U.S. Industrial Interest in Superconductivity

Newsletter abbreviations used:
SI = *Superconductor Industry*
SW = *Superconductor Week*

This Appendix lists current and emerging technological applications of superconductivity. It is designed to show areas of interest and *lack* of interest in the U.S. industrial community. Numbers and comments are appropriate to mid-1992.

LTS Wire and Magnets

The manufacture, development, and testing of sc wire, including cabling, is an integral part of the manufacture of sc magnets and sc magnet systems. The commercial sc wire field is entirely LTS in 1992. Industry is pushing hard to develop long lengths of HTS wire suitable for magnets. HTS current leads and pickup coils are being explored as replacements for their normal-metal equivalents in sc magnet systems. The uses of superconducting magnets include:

<u>MRI</u>

- About 3000 MRI sc magnets are in use worldwide (SI **4**, p.33, spring 1991). About $200 million per year (1990) in sc materials and magnets is being spent in the MRI industry (SI **3**, p. 33, spring 1990). MRI sales have grown rapidly: in 1989 sales were about $1 billion (1990 Electronic Market Data Book); for 1992, about 1100 MRI units were projected to be sold at a price of about $1.4 million each, defining a world market of about $1.5 billion annually (SW **6**, 3 Aug 92).
- A new MRI scanning technique, called echo-planar imaging, can reduce imaging time by up to a factor of 10 000; when clinically implemented, this should reduce cost and time to the patient. This, together with greater ease of use and flexibility, and the fact that more uses are being found, may mean that sales of MRI systems will accelerate (SI **4**, p.5, Summer 1991; Science **254**, 43-50 (1991)).

<u>Particle accelerators and other laboratory uses</u>

- The SSC will have a 54-mile circumference of sc magnets, containing more than 10 000 magnets and requiring 20 million meters of sc cable.
- The Relativistic Heavy Ion Collider will use 0.6 million meters of sc cable.
- Many other accelerators using sc magnets are operating in the U.S. Synchrotrons using sc magnets are being developed for use in X-ray lithography.
- Tens of thousands of sc magnets are used in a multitude of research applications (Physics Today **44**, p. 74, June 1991).
- This area is entirely government supported.

<u>Fusion</u>

- The Mirror Fusion Test Facility uses kiloton sc magnets; the International Thermonuclear Experimental Reactor (ITER) will use 16 yet larger sc magnets to generate a toroidal field.
- This area is entirely government supported; U.S. commercial interest is many years away.

<u>Magnetic energy storage (SMES and flywheel)</u>

- Three categories of SMES are in the design and development stage: micro-SMES for customers of utilities; mid-SMES for transmission and distribution; large SMES as a generation option to help out during overload periods (SW **6**, 13 July 92). According to EPRI, SMES may develop as the biggest user of sc wire after MRI. HTS micro-SMES are being discussed (SW **6**, 1 June, 15 June, and 14 Sept 92; SI **4**, pp. 7,8, Summer 1991).

- A U.S. company built an experimental 30 megajoule SMES system in 1983.
- A U.S. company is manufacturing and delivering LTS micro-SMES systems, which provide short term backup power (megawatts) to industrial users when they experience voltage sags and power failures of up to five seconds. The potential market is large since the devices would be installed at individual user facilities rather than at power substations. (SI **4**, pp. 7,8, Summer 1991).
- Mid-SMES units are being discussed for use in Maglev trains and wayside power stations for utility lines (SW **6**, 29 June 1992).
- At least one U.S. company, with internal funding, is experimenting with flywheel energy storage, which some claim should be superior to SMES in that long, quality wires are not needed. A unit typically would have HTS bearings, permanent magnets in the flywheel, and be lifted by an HTS material such as YBCO. The bearings are claimed to have 25 times less friction than other types of magnetic bearings. A program goal is 12-hour storage. (SI **5**, p. 5, 12 Aug 91; pp. 3,4, 16 Sept 91)
- Japan is pursuing a similar program.

<u>Magnetic ore separation</u>

- Although magnetic separation of ores is commercial in the U.S., sc magnetic separation is still primarily in the R&D phase. One U.S. company built and sold a unit in 1986, but sold no others. Another U.S. company modified this version and sold a unit to a U.S. kaolin mining company in 1991; this same company has a contract to supply a similar system to a European kaolin clay facility in the fall of 1992 (SI **5**, p. 10, summer 1992). Yet another U.S. company says that their sc magnets are used in ore separation (letter to author dated 22 January 1992).
- Water treatment and oil refining by sc magnetic separation are other areas of research interest.

<u>Magnetic levitation (maglev) in transportation</u>

- The Federal Railroad Administration (FRA) surveyed 60 U.S. companies in 1990 and found almost no interest in maglev transport, primarily because of the very high risk nature of the enterprise. A preliminary FRA report to Congress (1990) stated that maglev transport may be economically feasible in a limited number of domestic transportation markets. The National Maglev Initiative, administered by the FRA, awarded a modest amount in 1991 for feasibility studies, and Congress approved at the end of 1991 a seven-year $775M sc maglev demonstration project, which however probably will not be funded until about 1994. (SI **4**, p. 12, winter 1991; SW **5**, 4 Nov 1991; SI **4**, p. 39, summer 1991)
- An OTA report (SW **5**, 11 Nov 1991) is rather negative on maglev transport.
- The Association of American Railroads is very negative on the viability of transport by maglev (SI **3**, p. 9, fall 1990).
- The State of New York commissioned a report from a consortium of U.S. companies, which concluded that maglev transport would "spur economic development, save fuel costs, reduce pollution, and alleviate the state's transportation quagmire." The study argues that maglev transport should be economically viable in the NYC-Albany-Buffalo corridor. The barrier to progress, the report says, is financing. (SI **4**, p. 16, spring 1991; SW **5**, 5 Aug 1991)
- The proposed Anaheim-Las Vegas maglev line attracted only one bidder (1990), who would use permanent-magnet technology rather than sc magnet technology.
- The first maglev train to be built in the U.S. (between the Orlando airport and Disneyworld) will use conventional magnet technology.

Magnets in ship propulsion

- The Navy is conducting R&D in this field because superconducting propulsion systems are very quiet and thus hard to detect (the screw propeller is replaced by flowing seawater as propellant.) HTS offers the possibility of greatly increasing the efficiency of ship propulsion through lighter weight superconductors.
- One U.S. company has (1991) a $700K contract to upgrade the Navy's superconducting electro-magnetic thruster which has no moving parts.
- There is no apparent U.S. commercial interest in sc ship propulsion.

LTS Electronics

Potential applications exist in almost all facets of electronic circuitry. Practical applications are yet modest because of cooling requirements to liquid helium temperatures.

Integrated circuits

- Several U.S. companies (and NIST) have R&D programs in very fast sc circuitry. For example, LTS analog/digital converters have been built operating at better than 10^{10} samples per second; the fastest toggle flip-flop circuits are built from LTS (SW **6**, 2 March 1992).
- Single flux quantum logic has recently been shown to be an attractive way of designing sc integrated circuits, having the least heat dissipation of any sc circuits yet designed.

Voltage standards

- LTS Josephson array voltage standards are used in standards labs throughout the world, and by companies manufacturing precision electronic instrumentation. A collaboration between NIST and a U.S. company hopes to develop a lower-cost JJ array to open up a larger market.

SQUIDs

- SQUIDs for magnetometry have been commercially available for about two decades, but the market is yet small primarily because of the expense of LTS SQUID systems. Reduction in cost through HTS or improved cryocoolers could open up a large market. Nondestructive evaluation of metallic and composite structures with use of LTS SQUID magnetometers, having potential for a large market, has been demonstrated by a U.S. company. Recently developed monolithic thin-film HTS SQUIDs may be a path toward significant commercialization of SQUIDs.

HTS Materials and Electronics

A multitude of potential uses for HTS is being explored by a number of U.S. companies. Areas of activity include:

Electronics

- HTS interconnects will soon be commercialized. Superconducting interconnects among semiconductor chips is expected to improve performance by about a factor of three. With normal-metal interconnects, the wires have to be 25 to 40 micrometers wide in order to keep resistance low; with sc wires, linewidths need be just 1.5 to 2 micrometers. Instead of dozens of layers of interconnects, only two layers of sc are needed. Thus modules can be made both simpler and smaller (SW **5**, 9 Sept 1991).
- Microwave devices based on HTS are actively being developed by U.S. companies. The first commercial HTS thin film components - resonators and filters - became available in 1990. These have much lower surface resistances than those made from ordinary metals. They are simple, being single-layer films on substrates. High-power phase shifters, microstrip antennas,

coil resonators, and meander line resonators are among the components which have been developed. (SW **5**, 2 Dec 1991; **6**, 30 March 1992)

- Many U.S. companies are involved in the government-funded HTS Space Experiment. Devices in this program include delay lines, filters, multiplexers, oscillators, strip/ring resonators, microwave cavities, power limiters, phase shifters, IR bolometers, shields, thermal isolators, and Stirling-cycle coolers.

<u>Superconducting magnetic bearings</u>

- About 20 laboratories in several countries are working on HTS bearings. The materials are good enough but more engineering is needed. “Passive bearings are one of the most near-term applications [of HTS] that I see.” “We feel that bearings are probably one of the first bulk applications and one of the first HTS applications.” The field needs standardization of set-ups for rpm and levitation pressure testing. (SI **4**, pp. 22-28, summer 1991)

<u>Power transmission lines</u>

- The ad-hoc Industry Working Group on Power Applications of HTS issued a white paper “A National Program for the Superconducting Electric Power System of the Future” (April 1991) calling for a “banner” program funded jointly by industry and government “to provide an impetus and focus on development of all the major components of a superconducting power system, including motors, generators, transmission lines, transformer, and energy storage, each with specific HTS conductor characteristics and refrigeration systems.”
- DoE in 1992 began a five-year program in HTS emphasizing power transmission. EPRI in 1991 funded about $2.5 million on HTS power applications, and is planning to scale up.
- At least three U.S. companies, with funding from the government, are now developing HTS transmission cable under contract to the government. HTS wire longer than 30 meters and supporting 2000 amperes have been developed. (SW **5**, 14 October 1991)
- Advantages include environmental impact because sources of electric production can be placed far from users.

<u>Magnetic shielding</u>

- Magnetic shielding is used in medical diagnostics, physics research, and electronic security. In the low-frequency regime, where background noise is the strongest, conventional shields provide the least shielding effectiveness. New magnetic shields made of HTS materials show order of magnitude improvements in shielding.
- There seems to be limited U.S. manufacturing interest in magnetic shielding.
- Japan sells HTS shielding big enough to cover a human body. (SI **3**, p. 7, fall 1990)

<u>Superconducting motors</u>

- A 25-watt demonstration motor was built with HTS wire in 1990 by a U.S. company and has been running continuously since then. (SW **5**, 7 Oct 1991; SW **6**, 8 June 1992)
- Over 70% of the electrical energy used in almost any manufacturing facility is consumed by motors. Large motors (above 125 horsepower) are responsible for about one-third of all energy consumption, and lose 20 billion kilowatt hours of electricity in the U.S. annually. Converting from copper to sc coils in the rotor would reduce losses of a single 10 000 horsepower continuous-duty motor by 60%. Replacing the copper stator coils by sc would save yet more. (SW **6**, 13 July 1992)

Cryogen level sensors

- Several U.S. companies make cryogen level sensors from HTS materials; the current market is several million dollars per year.

Infrared detection

- U.S. companies have ongoing defense contracts to build infrared (IR) detectors for space applications. Large-area, multi-element arrays using HTS instead of semiconductors are being investigated as IR detectors; such arrays offer greater sensitivity over a wider range of IR wavelengths. Quality large-area devices are very expensive and difficult to make with semiconductor technology. (SW **5**, 23 September 1991)

Auxiliary Industries

The superconductivity industry supports and has helped to expand many auxiliary industries, including: thin film growth, deposition, and evaluation systems; cryogenic liquid production and delivery services; cryocooler manufacture (one U.S. company is gearing up to produce 10 000 cryocoolers per year at 77 K, mostly for CMOS chips, but with HTS also in mind (SI **4**, p. 13, spring 1991)); cryostat manufacture (some cryostats are made specifically for sc testing and characterization); and raw materials for manufacture of superconductors.

Appendix B. List of Companies Contacted

Company	Date Contacted	Date of Reply
American Magnetics	2 Oct 1991	18 Oct 1991
American Superconductor (ASC)	2 Oct 1991	25 Oct 1991
AT&T, Murray Hill	Nov 1990 31 July 1991	
Ball Aerospace	Nov 1990 26 Sept 1991	29 Jan 1991
Ball Communications	Nov 1990	12 Dec 1991
Battelle Columbus	2 Oct 1991	7 Oct 1991
Biomagnetic Technologies (BTI)	16 Nov 1990 31 July 1991	11 Dec 1990
Conductus	Nov 1990	7 Jan 1991
CPS Superconductor	2 Oct 1991	
Cryomagnetics	2 Oct 1991	
Eastman Kodak	 2 Oct 1991	Pre-Study Letter 22 Oct 1991
General Dynamics Space Systems	2 Oct 1991	1 Nov 1991
General Electric Medical Systems	2 Oct 1991	22 Oct 1991
Hauser	2 Oct 1991	
Hewlett-Packard, Loveland	 31 July 1991	Pre-Study Letter 20 Aug 1991
Hughes Microelectronics Center	31 July 1991	17 Sept 1991
Hypres	31 July 1991	13 Aug 1991
Hypres (bolometer group)	31 July 1991	27 Aug 1991
Intermagnetics General (IGC)	2 Oct 1991	27 Mar 1992
IGC/Advanced Superconductors	5 Feb 1992	10 Mar 1992

John Fluke Mfg.		Pre-Study Letter
	31 July 1991	1 Oct 1991
Keithley Instruments		Pre-Study Letter
	2 Oct 1991	11 Oct 1991
Lake Shore Cryotronics	15 Aug 1991	28 Aug 1991
Lockheed Missiles & Space		Pre-Study Letter
Lockheed Sanders	15 Aug 1991	29 Aug 1991
NRC	2 Oct 1991	23 Oct 1991
New England Electric Wire	2 Oct 1991	
Oxford Superconductor Tech	2 Oct 1991	11 Oct 1991
Quantum Magnetics	16 Nov 1990	11 Dec 1990
Research & Manufacturing Co. (RMC)	16 Nov 1990	21 Dec 1990
	26 Sept 1991	3 Oct 1991
Rockwell International	15 Aug 1991	20 Aug 1991
Supercon	2 Oct 1991	9 Oct 1991
Superconductor Technologies (STI)	2 Oct 1991	14 Oct 1991
Teledyne SC	2 Oct 1991	22 Oct 1991
Teledyne Wah Chang		Pre-Study Letter
	2 Oct 1991	
Wang NMR	5 Nov 1991	
Westinghouse R&D	Nov 1990	26 April 1991
Westinghouse S&T	31 July 1991	7 Aug 1991
Westinghouse S&T	15 Aug 1991	
Xerox Palo Alto	15 Aug 1991	23 Aug 1991

Appendix C. Sample Questionnaire

Company Name *(please correct if necessary):* AAA Corp.

1. Brief description of your company/division function:

2. Approximate number of full and part-time employees at your location: _____

3. The current and recent superconductivity programs at NIST/Boulder can be grouped as follows. Please check each program which is of direct use or value to AAA Corp.. [LTS = low-temperature superconductors, HTS = high-temperature superconductors]

_____ Development of measurement standards for LTS (J_c, H_c, ac loss)
_____ Development of LTS standard reference materials for critical current measurement
_____ Characterization of materials (copper, alloys) and effects (strain, magnetic coupling, cabling) in LTS magnet structures
_____ Development of LTS field measurement devices (SQUID magnetometers, infrared detectors)
_____ Development of LTS Josephson junction array voltage standards
_____ Development of other LTS devices such as A/D converters, flux quantum counters, and single-electron counters
_____ Development of methods for producing quality HTS thin films, HTS Josephson junctions, and electrical contacts to HTS materials
_____ Development of measurement and theoretical techniques for analyzing properties of HTS materials, such as magnetization, flux sites and pinning, and critical current limitations

If you checked none of the above, skip to Question 7.

4. Benefit to AAA Corp. from the NIST superconductivity programs (check all those which apply; your answers will not be identified with your company in the NIST report):

_____ Productivity of manufacturing was improved (through better testing capability, improved process control or process design, etc). If this was checked:
Approximate annual dollar savings as a result: $_______
Approximate annual labor saved as a result: Work-months per year______
_____ Ability to meet customer specifications was improved (because of better measurement capability, improved product quality or reliability, etc.)
_____ Research/development time was shortened. If this was checked, what was the approximate amount of time and labor saved?
Time (months) _____ Labor (total work-months) ______
_____ NIST superconductivity programs have been essential for marketing or contract work (e.g., traceability requirements, measurement assurance)
_____ Have a better understanding of the science, engineering, or technology of an existing or anticipated company product or process
_____ New directions for company/division R&D programs are anticipated or implemented
_____ Have marketed or expect to market a new product
Approximate or anticipated annual sales of this product: $_______

_____ Existing marketed product was improved
Approximate annual increase in revenue: $_______
_____ Have referenced, or plan to reference, NIST in advertising or promotion
_____ Enabled AAA Corp. to secure or apply for a grant or contract

If applicable, about how many dollars has your company saved because of NIST assistance in generic design or development, because you did not have to purchase instrumentation, other hardware or software, or provide new space? $_______

If applicable, about how many dollars has your company spent to implement the information or assistance from NIST? $_______

5. If you have requested service or collaboration from NIST, what was the reason? (Check as many as apply.)

_____ Needed NIST certification or wanted NIST recognition.
_____ NIST had the expertise that was difficult or impossible to get elsewhere.
_____ It was convenient (geographical, personal contact, quick response, etc.)
_____ Other ____

6. How have your customers benefitted from the NIST superconductivity programs?
_____ Improved features or capabilities of your company's products
_____ Improved reliability of your company's products
_____ Opened up new markets or directions for your customers
_____ Lower costs to your customers
_____ Other ____

7. What technological or other problems in superconductivity are barriers to progress at AAA Corp.?

8. How could NIST be of more benefit to your company?

9. Other comments?

Appendix D. Counting of Benefits

Correct assessment of benefits can be subtle. In this Appendix, we discuss situations where care must be exercised when comparing or adding benefits, and state how we have treated them for purposes of this report.

Savings in productivity or shortened R&D time is a benefit directly related to profit. Increased sales is usually a benefit, but not all the increased revenue is profit. The two benefits are not simply additive. But to ignore increased sales in this analysis because the profit margin is not known would be to grossly understate the real benefit in most cases. For example, the savings due to the NIST assistance is usually but a small fraction of the total cost of production and can be much smaller than the profit realized from increased sales.

The question then is how to incorporate the increased sales into the present analysis. There may be instances where sales price is only a few percent above the cost of production, but others where sales price is only weakly connected to cost of production. An example of the latter is when a new product based on a new idea or design is introduced, with little new capitalization required to produce it, and the price is simply based on what the market is likely to bear. For this report we choose an *average* profit margin of 100%, which is likely conservative. Thus, reported annual sales of $100K is interpreted here to imply annual profit of $50K. With this device, we are able then to add the benefits of increased sales to savings from improved productivity or shortened R&D.

Next we consider two hypothetical cases where care must be exercised to avoid counting a benefit twice.

A company has been marketing a device. In interaction with NIST the company learns how it can make the device more simply but with the same functionality. The company markets the modified device at a lower price, which generates increased sales and profits. Ideally, the company can estimate the increased sales profit and keep it separate from the savings from producing the device at lower cost. This would be two benefits, properly counted as such. However, if the survey respondent is aware only of the increased profit from the interaction and reports that figure both as increased revenue and cost savings, that is duplicate reporting and should be taken into account. Or suppose that the respondent reasons that the company could have improved the design without NIST assistance by having hired additional personnel with the expertise that NIST had. Since they did not have to do that, they have avoided additional labor costs. If they estimate and report a figure for that as well as for the other categories, the benefit would be multiply counted.

We have analyzed the responses to see whether any such cases might be present and concluded that there were none.