NISTIR 5409

ELECTRONICS AND ELECTRICAL ENGINEERING LABORATORY

1994 STRATEGIC PLAN

Supporting Technology for U.S. Competitiveness in Electronics

Electronics and Electrical Engineering Laboratory

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards and Technology
Electronics and Electrical Engineering Laboratory

April 1994

NIST

NIST SEEKS YOUR COMMENTS

EEEL reviews its plans regularly to keep them focused on the most important needs of the U.S. electronics and electrical-equipment industries. Comments on this plan are invited and should be sent to the following address:

Judson C. French, Director
Electronics and Electrical Engineering Laboratory
National Institute of Standards and Technology
Building 220 - Room B358
Gaithersburg, MD 20899
Telephone: (301) 975-2220
FAX: (301) 975-4091

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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

Bibliographic Information

Abstract

The U.S. electronics and electrical-equipment industries are outstripping available measurement capability with adverse effects on their international competitiveness. Improved measurement support is an essential part of any successful strategy for improving their competitiveness.

Among U.S. manufacturing industries, the electronics industry is the largest employer with 1.8 million employees and is virtually tied with the chemical industry for largest shipments of nearly $300 billion (1992). The electrical-equipment industry is also quite large, with shipments of nearly $50 billion (1990). U.S. competitiveness in many fields of electronic and electrical products has been declining. Improved competitiveness will require outstanding performance from manufacturers in every step required to realize a competitive product in the marketplace: research and development, manufacturing, marketplace exchange, and after-sales support. All of these steps are highly measurement intensive.

The Electronics and Electrical Engineering Laboratory (EEEL), within the National Institute of Standards and Technology, has identified the principal needs for improved measurement capability and other supporting technology in several important fields: semiconductors, magnetics, superconductors, low frequency, microwaves, lightwaves, power, video, electromagnetic compatibility, electronic data exchange, and national electrical standards. This document describes EEEL's strategic plan for a response to these needs. That response is related to important national goals for a strengthened economy and improved international competitiveness. This plan was developed in consultation with U.S. industry and other NIST Laboratories.

Keywords

competitiveness, electrical power, electronics, magnetics, measurements, microwaves, optical-fiber communications, semiconductors, video

Ordering

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ORGANIZATION OF THIS PLAN

The first five sections of this plan explain the overall mission of EEEL, the goals that it serves at the national level, the deliverables that it provides, and the customers that it serves. A special emphasis is given to EEEL's primary customers: the electronics and electrical-equipment industries.

MISSION
NATIONAL GOALS SERVED
DELIVERABLES
MEANS OF DELIVERY
CUSTOMERS SERVED

The next sections show how EEEL's program is structured to serve EEEL's customers, and states the assumptions made in the plan about the availability of future resources to implement the plan.

EEEL'S PROGRAM STRUCTURE
RESOURCE ASSUMPTIONS

The following sections describe the competitiveness forces that drive EEEL's program, and the strategic directions that EEEL is taking in response. These directions are expressed in two ways: directions that are common across many of the fields of technology that EEEL supports; and directions that are particularly important to individual fields of technology. Predominant, new, or changing directions for the program are emphasized. These two sections on strategic directions are the core of this strategic plan.

COMPETITIVENESS DRIVING FORCES
STRATEGIC DIRECTIONS ACROSS FIELDS
STRATEGIC DIRECTIONS WITHIN FIELDS

The final sections provide additional information. A survey of EEEL's customers shows the full scope and mix. EEEL's approach to strategic planning is described, along with the primary documents that EEEL develops for planning. Finally, EEEL's methods for measuring technical program progress and economic impact are described; and the findings of all analytical impact studies completed since EEEL last published its strategic plan in 1991 are summarized.

CUSTOMER SURVEY
PLANNING
MEASURING PROGRESS AND IMPACT

References and supplemental information are provided at the end of the plan in the "Endnotes".

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SUMMARY

The Electronics and Electrical Engineering Laboratory focuses on strengthening the U.S. economy by improving the competitiveness of the U.S. electronics and electrical-equipment industries. The electronics industry ships nearly $300 billion of products annually. It is one of the two largest manufacturing industries in the United States and provides more high-paying jobs than the next three largest industries combined. The electrical-equipment industry ships nearly $50 billion of products. The competitiveness of these two industries is essential in meeting national goals for communications, computing, transportation, energy, environment, defense, education, medicine, and manufacturing.

EEEL's strategic approach is metrology based and industry oriented. EEEL searches out and evaluates needs arising in all steps that industry must complete to realize competitive products in the marketplace: research and development, manufacturing, marketplace exchange, and after-sales support. EEEL's aim is to find the needs that are of highest economic impact, that industry cannot well meet without NIST's help, and that NIST can meet with deliverables appropriate to its mission. EEEL emphasizes research-supported measurement capability as the service of highest leverage. It enables industry to pursue its own directions with enhanced effectiveness.

The supported industries are pursuing sweeping changes including rapid exploitation of higher levels of technology, shorter product development cycles, increased product diversity, lower prices per function, and broader entry to mass commercial and consumer markets. These changes cut across the fields that EEEL serves: semiconductors, magnetics, superconductors, low frequency, lightwaves, microwaves, video, power, electromagnetic compatibility, and electronic data exchange. The changes motivate a dozen cross-cutting strategic directions for EEEL. Here are important examples.

Integration: Manufacturers are pursuing integrated circuits as the principal means of implementing increased functionality at lower cost. Integration has been implemented for semiconductors first, with magnetics, optoelectronics, and superconductors following. Integration requires hundreds of processing steps and mandates extraordinary process control. EEEL is responding with a greatly expanded emphasis on measurements for integrated-circuit manufacturing, with the ultimate goal of supporting active, real-time process control that enables making the product right the first time.

Higher Frequencies: Manufacturers are pursuing higher frequencies to provide increased information capacity for wireless portable, mobile, and new Personal Communications Services, for faster computers, and for intelligent vehicle/highway systems with navigation, collision-avoidance, and traffic-light-control services. Microwave technology is the essential next step for such products. Similarly, lightwave technology is the core cable technology for optical-fiber communications systems for the National Information Infrastructure. EEEL is responding with major efforts focused on critical measurement problems presently limiting component development.

Higher Accuracies: Manufacturers are pursuing rapid commercialization through collaborative development and concurrent engineering. They are also pursuing product diversity through flexible manufacturing to compete on economies of scope, as well as scale. These aims require improved measurement capability for better *communication* among collaborators and for better *control* during flexible manufacturing. The principal needs are higher accuracies and measurement efficiencies for more measured quantities. EEEL is responding with measurement accuracies traceable to fundamental atomic constants, with digital measurement techniques susceptible of efficient automation, and with strategies for minimizing the number of measurements required for product characterization.

INTRODUCTION

The Electronics and Electrical Engineering Laboratory (EEEL), working in collaboration with other NIST Laboratories, is providing supporting technology that is critical to the competitiveness of the U.S. electronics industry and the U.S. electrical-equipment industry.

Among U.S. manufacturing industries, the electronics industry is the largest employer (1.8 million in 1992) and is in a virtual tie with the chemical industry for largest shipments (nearly $300 billion for 1992).[1] The electronics industry exerts extraordinary influence on the performance of every other U.S. industry.

For the electrical-equipment industry, U.S. shipments are $48 billion (1990).[2] Among the products included in those shipments are the various types of equipment used by the electric utilities. They provide $187 billion of electricity annually (1992).[3]

These industries are battling for market share in increasingly competitive international markets. The United States is experiencing an unfavorable and worsening balance of trade for electronic products overall.[4] The consumer electronics market has been lost; and the computer market, traditionally a strong area for the United States, is showing a declining balance of trade. The electrical-equipment industry is also struggling against strong competitors in many market segments.

There are many factors contributing to this situation -- social, economic, and technical. One of the most important is technical: lack of adequate measurement capability. Both the electronics industry and the electrical-equipment industry are outstripping the available measurement capability required for competitiveness. The lack of adequate measurement capability adversely affects virtually every step required to realize competitive products. Adversely affected are product performance, price, quality, compatibility, time to market, and implementation of new management strategies, to name a few factors.

NIST can help by providing measurement capability that supports the efforts of U.S. industry to improve its competitiveness. This strategic plan describes the broad directions of EEEL's response to industry's needs for *EEEL's five-year planning period from FY 1994 through FY 1998.* These broad directions are responsive to EEEL's detailed assessments of those needs, developed in consultation with U.S. industry and other NIST Laboratories. The most recent assessments are contained in *Measurements for Competitiveness in Electronics*, published in April 1993.[5] EEEL implements its strategic plan through programmatic action described in its *1994 Program Plan*, published in December 1993.[6]

MISSION

EEEL's mission is to promote U.S. economic growth through improved international competitiveness, by providing measurement capability of high economic impact focused primarily on the critical needs of the U.S. electronics and electrical-equipment industries. In fulfilling this mission, EEEL strives to provide leading-edge measurement capability supportive of the each of the major steps required to realize competitive products in the marketplace: research and development, manufacturing, marketplace exchange, and after-sales support. Good measurement support is essential for accelerating the commercialization of technology, a primary requirement for improved U.S. competitiveness.

NATIONAL GOALS SERVED

EEEL's program supports a broad spectrum of national goals. President Clinton has placed a strong emphasis on economic growth through improved U.S. competitiveness -- the primary focus of EEEL's program. He has also identified specific national goals that support economic growth and that seek to improve the quality of life for U.S. citizens. Achieving many of these goals is highly dependent on the availability of electronic and electrical products with high performance, high quality, and affordable costs. Several of the goals for which this dependency is especially overt are listed in

Table 1: PRESIDENTIAL GOALS DEPENDENT ON ELECTRONIC AND ELECTRICAL PRODUCTS

Societal Service / Presidential Goal	Explanation
Communications	
Information Highway[7(a)]	"development of a broadband, interactive telecommunications network linking the Nation's public schools, libraries, health care facilities, governments, and other public information producers"
Transportation	
Smart Cars/Smart Highways[7(f)]	"improve traffic control systems, warn drivers of dangerous situations, and make more efficient use of the existing highway infrastructure", using "state-of-the art communications, warning systems, electronic displays, and computer technology"
Air Traffic Control Modernization[7(h)]	"reduced air travel delays, more efficient aircraft routing, fewer accidents and more cost-effective operation of the air traffic control system" through use of "new radars, computers, controller workstations and communications equipment, and supporting R&D"
Magnetic Levitation and High-Speed Rail Transportation[7(g)]	"meet the transportation needs of several of the nation's high-density corridors"
Energy	
Energy/Alternative Fuel Vehicles[7(d)]	"acquisition of and/or conversion to additional alternative fuel vehicles in the Federal fleet"
Energy/Building and Industrial Conservation[7(c)]	"demonstrate or accelerate the commercial acceptance of advanced energy conservation technologies and products"
Federal Buildings Energy Efficiency[7(e)]	"to improve energy efficiency in facilities throughout the Federal Government"
Environment	
Environmental Technology[7(j)]	"develop more advanced environmental systems and treatment techniques that can yield environmental benefits and increase exports of 'green' technologies"
Green Energy-Efficiency Programs[7(b)]	"encourages the Nation's business community to seek ways of increasing energy efficiency"
Weather Service Modernization[7(i)]	"more accurate and timely forecasts of severe weather events" through systems with "new observation systems such as doppler radars and weather satellites"

Table 1, along with brief explanations drawn from the President's document, *A Vision of Change for America*.[7] These goals address principally the societal services of communications, transportation, energy, and environmental improvement and monitoring. The Information Highway, listed under the Communications heading in the table, is also referred to as the National Information Infrastructure.

DELIVERABLES

Table 2: DELIVERABLES
Measurement Capability
absolute accuracy
reproducibility
materials reference data
Technology Development
Fundamental Research

EEEL provides three major classes of deliverables. They are listed in Table 2 and are discussed below with a view to explaining their importance and EEEL's priorities for them.

Measurement Capability

EEEL focuses the largest part of its resources on the development of measurement capability for two principal reasons:

> Measurement capability has very high impact on U.S. industry because measurement capability supports manufacturers in addressing many of the challenges that they face in realizing competitive products in the marketplace. A detailed discussion of the dependence of competitiveness on measurement capability is provided in Chapter 1 of *Measurements for Competitiveness in Electronics*.
>
> NIST bears the official imprimatur of the U.S. Government as the lead agency for measurements.

EEEL focuses on developing measurement capability that is beyond the reach of the broad range of individual companies. Thus, EEEL does not develop measurement capability that companies can provide for themselves. Companies seek NIST's help for several reasons:

> They may feel that NIST's special technical capability for measurement development is needed.
>
> They may feel that NIST's acknowledged impartiality is needed for diagnosing a measurement problem affecting the industry broadly or for achieving adoption of a solution across the industry.
>
> They may feel that they themselves cannot develop measurement capability needed by the industry broadly because they cannot individually capture the returns of the costs of development.

These reasons, and others, are reviewed in detail in Chapter 2 of *Measurements for Competitiveness in Electronics*, beginning on page 21.

Within the area of measurement capability, EEEL places its highest priority on delivering absolute accuracy. This emphasis reflects NIST's unique role as *the* national reference laboratory for measurements. Support for absolute accuracy may require a documented measurement method, a special measurement device, a reference standard to assure the accuracy of the measurement method, and a means of delivery, such as a measurement assurance program or a calibration service. A measurement reference standard may be a specially prepared material, such as a material of known purity, or an electronic device that produces or responds to the measured quantity of interest with a demonstrable degree of accuracy.

EEEL places its second highest priority on delivering reproducible measurement capability. Reproducible measurements repeat measured values reliably but do not necessarily have high absolute accuracy. Achieving reproducible measurements may also require a documented measurement method, a special measurement device, a reference standard, and a means of delivery.

EEEL also develops measured materials reference data on the electronic properties of materials. EEEL undertakes this work if NIST's special measurement skills are needed for development, or if NIST's evaluation and imprimatur are needed for wide acceptance. However, when these special conditions do not apply, EEEL prefers to provide industry with measurement capability that industry can use to develop the data, maximizing EEEL's leverage.

Technology Development

EEEL regularly engages in technology development that directly supports its measurement mission. For example, as part of developing or delivering new measurement capability, EEEL may find it necessary to build a special instrument or an integrated circuit that embodies the new capability. The technology realized in that instrument or circuit is transferred to the private sector, along with the associated measurement capability. Industry may modify the technology for incorporation in commercial products. Also, EEEL sometimes develops technology used for analyzing measured data. Examples include test strategies for complex electronic systems and expert-systems analyses for semiconductor processing lines.

EEEL engages in only limited technology development that extends beyond its measurement mission. EEEL limits the fraction of its resources so applied to about 10 percent of its total. For a technology-development project to be undertaken, it must offer unusually high impact. Also, it must give rise to special reasons for EEEL to be the performer. For example, the project may have originated with a NIST staff person and show unique prospects of high value, or it may require facilities or capabilities available only at NIST. An example is the development of selected process technology for semiconductor manufacturing, such as silicon-on-insulator process technology.

There are important reasons why EEEL limits the technology development that it undertakes outside of its measurement mission:

> EEEL generally finds that measurement capability has the highest impact among the deliverables that it can provide.
>
> EEEL's funding level is far short of that required to meet the principal measurement needs of the U.S. electronics and electrical-equipment industries. Therefore, any technology development undertaken outside of the measurement mission reduces the level of measurement support that EEEL can provide to U.S. industry.
>
> Other organizations exist to fund technology development, and some have considerable resources. Thus, the additional resources that EEEL could provide would not be significant. These organizations include NIST's own Advanced Technology Program ($200 million per year

beginning in FY 1994), the interagency Technology Reinvestment Project ($500 million per year beginning in FY 1993),[8] and many of the programs of other Federal agencies.

An example of a major technology-development project to which EEEL and other parts of NIST are contributing is electronic data exchange. This is an international effort. A key goal is the development of standard data structures for describing electronic components that support an electronic marketplace. These data structures will support product design, manufacturing, marketplace exchange, and after-sales support (servicing). Even though this project is not focused on measurement development, EEEL's role has a measurement character; EEEL will develop methods for testing proposed schemes for data exchange. This project is described on page 42.

Fundamental Research

EEEL defines fundamental research by the nature of the work conducted, not by the reason for undertaking it:[9]

> Fundamental research is the pursuit of the discovery or the understanding of the fundamental phenomena of nature.

EEEL conducts fundamental research as an integral part of many of its measurement-development projects. This is not surprising, since new measurement capability is generally developed at the leading edges of science and technology. Further, EEEL endeavors to maintain a fundamental-research effort in every broad program area. Such research is an important means of nucleating pathbreaking measurement capability. For example, EEEL laid the bases for the current Josephson voltage standard with two successful theoretical inquiries: one on the interactions of series arrays of Josephson junctions, and the other on chaos in Josephson junctions.

Table 3: MEANS OF DELIVERY

Communications	**FY93**
publications	214
software requests	279
talks	290
consultations	1710
visits	420
visitors	1000
meetings	
attendees	900
contributors	65
Joint Activities	
standards organizations	
staff participating	47
memberships	90
professional societies	
memberships	280
cooperative research	94
consortia (incl. forming)	3
guest scientists	42
Paid Services	
custom measurement development	159
standard reference materials	103
calibration service customers	450
training courses	11

Most of the fundamental-research projects that EEEL pursues are focused on topics likely to have outcomes benefitting measurement development for U.S. industry. That is, EEEL conducts *directed fundamental research*. EEEL does not bound the amount of directed fundamental research that it conducts to support its measurement mission. The amount conducted is determined by the needs of the individual projects pursued. For a given project, that amount may be 80 percent of project resources or next to nothing.

EEEL conducts some fundamental research that is *not* directed toward potential outcomes benefitting measurement development. The criteria for identifying a suitable project are similar to those for technology development: unusual opportunity for high impact, and some special reason for EEEL to be the performer. Examples include EEEL's work on determining values for the fundamental atomic constants, such as the fine-structure constant and the gyromagnetic ratio of the proton.

MEANS OF DELIVERY

EEEL provides its deliverables by three principal means, as shown in Table 3: communications, joint activities, and paid services.[10] FY 1993 levels of activity are shown in the table. These means of delivery involve regular interactions with industry, government agencies, and educational institutions. The interactions are essential to planning as well as to delivery. Over recent years, the levels of activity associated with the various means of delivery have varied up and down but not with distinct trends. All continue to be important to effective delivery. An examination of the workload on staff members indicates that they are operating at capacity in the number of technology-transfer activities that they can handle.

CUSTOMERS SERVED

EEEL serves the electronics and electrical-equipment industries as its primary customers. These two industries are discussed briefly below. EEEL also serves government agencies (Federal, state, and local), educational institutions, and, through them all, the general public. A survey of the scope and composition of EEEL's customers is provided in the section "Customer Survey" on page 45.

Table 4: SERVICES

Information
- generation
- manipulation
- transfer
- storage
- display

Energy
- generation
- control
- transfer
- storage
- conversion

The products of the electronics and electrical-equipment industries provide two principal classes of services -- information and energy -- as shown in Table 4. The products of the electronics industry provide principally information services but also a significant number of energy services. For example, lasers generate light for carrying information in optical fibers; lasers also generate light as energy for cutting and welding, which are energy services. Similarly, semiconductor devices store and manipulate information in computers; they also control energy in power systems and in diverse applications, such as manufacturing processes and aircraft control. In contrast, the products of the electrical-equipment industry provide energy services virtually exclusively.

Electronics Industry

The electronics industry and the chemical industry are the two largest manufacturing industries in the United States, as shown in Table 5.[11] Each has estimated annual shipments approaching $300 billion per year for 1992; the difference between them is not significant, given the different ways the values were determined. The electronics industry is the largest employer with 1.8 million workers, more workers than the next three largest manufacturing industries combined.

Table 5: LARGEST U.S. MANUFACTURING INDUSTRIES (1992)

Industry	Shipments ($billions)	Employment (thousands)
Electronics[11(a)]	288	1,808
Chemical[11(b)]	279	853
Automotive[11(c)]	227	873
Petroleum Refining[11(d)]	130	72
Aerospace[11(e)]	113	652

The shipments and employment of the electronics industry over a five-year period from 1988 to 1992 are shown in Table 6. The shipments are in current dollars and reflect a compound annual growth rate of 3.5 percent. Over the same period, the price deflator for the Gross Domestic Product increased at a compound annual growth rate of nearly 3.9 percent.[12] Thus, removing the effects of inflation would suggest that the shipments of the industry were essentially flat in real terms over this period. Employment in the electronics industry fell with a compound annual growth rate of -3.7 percent during this period.

Table 6: ELECTRONICS INDUSTRY OVER FIVE YEARS

Year	Shipments ($billions)	Employment (thousands)
1988	251	2,100
1989	260	2,086
1990	273	2,002
1991	273	1,911
1992	288	1,808

The electronics industry produces a broad spectrum of products. This spectrum is shown in Table 7 using a structure employed by the industry itself, through the Electronic Industries Association. The distribution of the products is expressed as the percentage of total shipments of all U.S. electronic products. The percentage values in the right-most column are for the largest breaks. The percentage values in the columns more to the left are for progressively finer breaks. The year represented is 1990. This is the middle year of the five-year period addressed in Table 6 and is thus likely to be representative of the period.[13] The three largest categories are electronic components, communications equipment, and computers and their peripherals. A fourth large category, electronic-related products, shown at the bottom of the table, is not a homogeneous category. Rather, it is a special category that picks up electronic products made as part of other products and not captured at market interfaces in the other categories. Considering the table as a whole, the dominance of information services in electronic products is clearly evident.

In addition, electronic products are built into the products of many other industries, including, for example, virtually all motor vehicles and aerospace products. Electronic products are also built into virtually all manufacturing equipment used in any industry. The electronics industry exerts extraordinary influence on the performance of every other U.S. industry and affects the lifestyle of every U.S. citizen.

Electrical-Equipment Industry

The electrical-equipment industry is considerably smaller than the electronics industry but is still quite large. This industry shipped $48 billion of products in 1990.[14]

The distribution of the electrical products for 1990 year is shown in Table 8.[15] Again, the percentage values in the right most column represent the largest breaks. The largest categories are electrical equipment used to transfer energy and to control energy. These products are used by the electrical utilities to provide $187 billion of electricity annually (1992).[16]

Note that a third category could be formed by combining motion and generation which employ similar technology. The combination would have a size comparable to that for control. Based on an analysis for 1985, which is the most recent year for which such an analysis is available, motors consumed about 60 percent of all electricity used.[17] This percentage, if still valid in 1992, would suggest a consumption level of $112 billion for that year. Motors are thus of considerable economic significance for at least two reasons: value of shipments made, and value of electricity consumed.

The use of electrical equipment in the automotive industry is so great that separate breakouts have been provided in several locations in the table, where those breakouts could be determined. Somewhat more than 14 percent of all electrical equipment is used in automotive products.

Table 7: U.S. SHIPMENTS OF ELECTRONIC PRODUCTS (percent, 1990)

Electronic Components[13(a)]			21
electron tubes		1	
solid-state (semiconductor)		8	
integrated circuits	6		
other (wafers, packages, transistors, diodes, rectifiers, etc.)	2		
parts		4	
other components[13(b)]		8	
printed-circuit boards	2		
printed-circuit assemblies	3		
other (microwave components, power supply converters, cables, etc.)	3		
Communications Equipment			25
commercial, industrial, and military communications equipment[13(c)]		6	
mobile and portable communications equipment	2		
space satellite communications systems	1		
other receivers and transmitters, except amateur and citizens	1		
other (fiber optics, antennas, amateur, citizens, etc.)	2		
telephone and telegraph equipment[13(d)]		6	
central office switching equipment	2		
carrier line equipment	1		
other (other switching, switchboards, modems, telephone sets, etc.)	3		
intercommunications systems, alarm systems, and traffic control equipment[13(e)]		1	
broadcast, studio, and related electronic equipment[13(f)]		1	
search and detection, navigation and guidance systems and equipment[13(g)]		12	
radar systems and equipment	3		
missile and space vehicle equipment	2		
navigation systems	2		
counter measures equipment	1		
light reconnaissance and surveillance systems	1		
special electronic and communication intelligence equipment	1		
other (sonar, specialized command and control, etc.)	3		
Computers and Peripherals			21
computers[13(h)]		11	
general purpose	9		
special purpose	1		
parts for computers	1		
peripherals[13(i)]		10	
magnetic and optical data storage devices and media	3		
printers and plotters	2		
terminals	1		
parts for peripheral equipment	2		
other (other input/output devices, etc.)	1		
Industrial Electronics[13(j)]			7
control and processing equipment		4	
control equipment	2		
processing equipment	1		
display and control instruments	1		
testing and measuring equipment		2	
other (nuclear electronic, robots, etc.)		2	
Electromedical Equipment[13(k)]			3
diagnostic		1	
other (patient monitoring, irradiation equipment, therapeutic equipment)		2	
Consumer Electronic Products[13(l)]			3
television receivers		2	
other (recorders, phonographs, radio/TV chassis, audio/video tape, etc.)		1	
Electronic-Related Products and Services[13(m)]			20
aerospace equipment (aircraft, missiles)		10	
automatic controls, industrial apparatus, and other instruments		-	
systems integration and computer services		8	
motor vehicles		1	
electronic-related office equipment		1	
Total			100

Table 8: U.S. SHIPMENTS OF ELECTRICAL EQUIPMENT (percent, 1990)			
Electrical Supply Equipment			78
generation		5	
generators and parts	3		
automotive generators and parts	2		
transfer		44	
transformers	9		
insulation	1		
wire	15		
wiring devices	15		
automotive wiring and distribution devices	4		
control		19	
switchgear	11		
relays, industrial controls, and apparatus	3		
automotive electrical equipment	5		
storage		10	
storage batteries	7		
primary batteries, wet and dry	3		
Electrical Conversion Equipment			22
motion		14	
motors and parts	12		
automotive motors and parts	2		
light		6	
heat		2	
elements and electrodes	1		
automotive spark plugs	1		
electrolytic action		1	
Total			100

U.S. Competitiveness

World markets and U.S. competitiveness in those markets for individual fields of electronic technology have been described in detail in *Measurements for Competitiveness in Electronics*. Rather than repeating that description here, the reader is referred to that source. The organization of the fields of electronic technology addressed in that document is readily related to the organization of the fields of technology in this strategic plan.

Classifying Electronic and Electrical Products

Electronic and electrical products can be classified using a variety of different strategies. Five key important strategies are shown in Table 9. The strategies in columns (1) and (2) are closer to the underlying technologies used to make the products. The strategies in columns (3), (4), and (5) are closer to the individual products as sold in the marketplace. These several strategies are useful for understanding the scope and nature of electronic products. The strategies are also useful for describing EEEL's strategic directions and will be referred to throughout this plan.

Electronics Industry

The approach used for the electronics industry in Table 7 starts with the strategy in column (3) and separates out the two dominant categories: components and equipment (with an admixture of systems

(1) Key Material	(2) Frequency of Operation	(3) Stage of Assembly	(4) Basic Service or Function	(5) Societal Service or Function
conducting	low frequency	materials	information	communications
normal conducting	dc	components	generation	computing
semiconducting	audio	discrete	manipulation	manufacturing
superconducting	radio frequency	integrated	transfer	health/medicine
insulating	microwaves	circuit assemblies	storage	entertainment
magnetic	lightwaves	equipment	display	transportation
optical	X-rays	systems	energy	defense
optoelectronic			generation	energy
magneto-optic			control	environment
dielectric			transfer	education
thermionic			storage	housing
electro-chemical			conversion	

Table 9: STRATEGIES FOR CLASSIFYING ELECTRONIC AND ELECTRICAL PRODUCTS

in the latter). The components category is then broken down into categories that can be identified with discrete components (tubes, other solid-state component, parts, and others), integrated components (integrated circuits), and circuit assemblies (principally of circuit boards filled with discrete and integrated components). The equipment category is broken down largely by the strategy in column (5), with the following correspondences: industrial electronics (manufacturing), electromedical equipment (health/medicine), consumer electronic products (entertainment), aerospace equipment (transportation/defense), and a few other product lines that correspond again to the categories already mentioned.

Electrical-Equipment Industry

The approach used for describing the products of the electrical-equipment industry in Table 8 corresponds very closely to the strategy in column (4): basic service or function. This strategy works well for this industry because electrical products are mostly single-function products, like motors and transformers. They differ from electronic products, such as computers and communications equipment, which perform complex and diverse functions.

EEEL'S PROGRAM STRUCTURE

EEEL describes the structure of its program using a combination of the strategies in columns (1), (2), (4), and (5). Because the strategies in columns (1) and (2) correspond closely to the underlying technologies, they are especially useful for classifying work that provides infratechnology support to the electronics and electrical-equipment industries. It is for this reason that these two strategies were used for most of the principal categories. However, the strategies in columns (4) and (5) have been found helpful in making needed distinctions, particularly in the finer structure of the program.

The resulting structure is shown in Table 10. For simplicity, EEEL refers to this structure as the *fields of technology* served in the electronics and electrical-equipment industries. The table includes both the fields that EEEL addresses currently, and the fields that EEEL plans to address in future years. Almost all of these fields are seeing rapid advances in technology, in either product technology or manufacturing technology or both. They are all the subject of current or foreseeable intense competitive pressures. They are increasingly interdependent technologies; success in any one of them is generally tied to success in one or more of the others.

Because of this interdependency, it is not possible to create an entirely separable set of categories to describe these technologies and the products made from them. The arrangement in Table 10, however, has been found workable. In this scheme, products are generally associated with the first applicable category on the list, as described in the following several paragraphs.

Table 10: FIELDS OF TECHNOLOGY SERVED (CURRENT AND FUTURE)

Fields	
semiconductors	
silicon	current
compound semiconductors	current
magnetics	
magnetic information storage	current
magnetic sensing	current
power materials	future
superconductors	
low temperature	current
high temperature	current
low frequency	
radio frequency	current
audio frequency	current
direct current	current
microwaves	
microwave signal processing	current
microwave computing	current
microwave transmission	current
lightwaves	
lasers	current
optical-fiber communications	current
optical-fiber sensors	current
optical information storage	future
optical signal processing	future
optical computing	future
computers	future
video	
vision	future
signal processing	current
transmission	current
information storage	current
displays	current
power	
generation	future
transmission	current
control	current
storage	future
conversion	current
Cross-Cutting Fields	
electromagnetic compatibility	current
electronic data exchange	current
national electrical standards	current

The three materials categories that lead the list (semiconductors, magnetics, and superconductors) represent measurement support provided for materials, discrete components, and integrated components for which the key material from which they are made seems the most convenient way of classifying the technology employed.

The three frequency-based categories (low frequency, microwaves, and lightwaves) that follow represent measurement support for materials, discrete components, integrated components, and equipment for which frequency seems the best way of classifying the technology employed.

The computer category provides a location for measurement support for equipment and systems important to computers and their peripherals and thus extends beyond the measurement support provided for materials and components under semiconductors and magnetics.

The video category focuses on measurement support for integrated components, equipment, and systems peculiar to video and thus extends beyond the measurement support provided for the more broadly applicable component technologies addressed in earlier entries in the table.

The power category focuses on measurement support for materials, equipment, and systems of principal interest to the electrical-equipment industry. It could also have been called the energy category.

Finally, three cross-cutting fields are shown. Electromagnetic compatibility focuses on measurement support for nearly every other category located higher in the table. Electronic data exchange focuses on test methods for evaluating data systems that support the development and manufacture of the products from virtually all other fields of technology in the table. An example is automated component descriptions to support the manufacturing of electronic and electrical products. National electrical standards focus on developing and maintaining measurement reference standards for the most fundamental quantities, such as dc (direct-current or zero-frequency) voltage, dc current, and dc resistance. These standards enable achieving high levels of absolute accuracy in measuring these quantities. They also provide reference values used to support the measurement of related ac (alternating-current or above-zero-frequency) quantities up to very high frequencies. In this way, the national electrical standards support the products of virtually all other fields of technology in the table. These national electrical standards underpin the national measurement system for electrical quantities. These standards also support U.S. participation in the determination of international electrical standards. They are discussed further on page 44.

EEEL provides some measurement support for all of the technologies marked "current" in Table 10, even if those efforts are small ones. EEEL sees a need to provide support for the technologies marked "future" in the table but lacks the resources to launch more than a pilot effort.

EEEL collaborates with other NIST Laboratories in providing needed support since their special skills in areas such as chemistry, materials, mechanical engineering, and computer software are also needed in service to the electronics and electrical-equipment industries. As for any industry, the electronics and electrical-equipment industries require a broader diversity of support than any one NIST Laboratory can provide. It is not unusual for EEEL to have 50 collaborative activities underway with other NIST Laboratories at any given time.[18]

RESOURCE ASSUMPTIONS

FY 1993 Resources

EEEL's funding and staff resources for FY 1993, the most recently completed year, are shown in Table 11. Base funding is provided by the Congress directly to NIST for the programs conducted in the NIST Laboratories. Non-base funding comes from multiple sources, but predominantly from three sources: funding transferred from NIST's Advanced Technology Program for support of its programs, funding transferred to NIST by other Federal agencies for the development of measurement capability supporting their programs, and funding provided by U.S. industry and other agencies for calibration services.

Plans for Growth

For FY 1994, EEEL anticipates small increases in its funding to the levels shown in the top part of Table 12. To provide the basis for this strategic plan, which covers the five-year planning period from FY 1994 through FY 1998, EEEL must make assumptions about future funding levels. EEEL's assumptions are these:

(1) The President will succeed in his goal of increasing NIST's base funding for the Laboratory programs by approximately a factor of 2 (in constant dollars) from FY 1993 to FY 1997, and NIST's funding will continue at that level in constant dollars in FY 1998.

(2) EEEL will share in the NIST increase in proportion to its present base level. This is an EEEL assumption for planning purposes. EEEL's level may be somewhat lower.

(3) EEEL will succeed in reducing its dependency on non-base funding to 20 percent or less during the planning period.

(4) The National Semiconductor Metrology Program, funded at a level of $25 million per year as called for by the Semiconductor Industry Association, will be implemented at NIST during the planning period.

Table 11: FY 1993 RESOURCES

Funding	$millions	percent
base	23.7	56
non-base		
from NIST[1]	2.8	6[4]
from outside NIST		
development[2]	13.2	31
services[3]	2.8	7[4]
total	42.5	100
Staff	number	percent
paid		
full-time permanent	298	77
other	45	12
total paid	343	89
unpaid		
guest scientists	42	11
total unpaid	42	11
total	385	100

Notes on Funding
[1]71 percent from Advanced Technology Program
[2]87 percent from other Federal agencies
[3]78 percent from calibrations services
[4]difference due to rounding more exact dollar values

The resulting funding levels for FY 1998 are shown in the top part of Table 12, expressed in constant FY 1994 dollars. These levels reflect a major increase in base funding and a smaller increase in total funding. Associated with the increases, EEEL anticipates growth in its staff of less than 10 percent. The bottom part of Table 12 shows EEEL's planned distribution of base funding among the fields of technology that constitute its major program elements.

Table 12: PLANS FOR GROWTH BY FIELD

	(millions of FY 1994 dollars)	
Funding Levels	**FY 1994**	**FY 1998**
base	28.1	47.2
non-base	17.1	10.0
total	45.2	57.2
Base Funding Distribution		
semiconductors	6.5	15.7
magnetics	0.9	2.0
superconductors	4.2	4.0
low frequency	2.0	3.0
microwaves	3.9	5.6
lightwaves	5.7	6.2
video	0.6	2.0
power	1.2	1.8
electromagnetic compatibility	1.0	2.0
electronic data exchange	0.3	2.0
national electrical standards	1.8	2.9
	28.1	47.2

Funding Shortfall

If the increased level of resources assumed for FY 1998 can be realized, it will be immensely helpful in increasing the capacity of EEEL to meet the measurement needs of the electronics and electrical-equipment industries. This strategic plan shows how EEEL will use those resources.

However, the resources that NIST applies *agency wide* to address the measurement needs of the electronics and electrical-equipment industries would have to be increased by a factor of at least five, relative to FY 1994 levels, just to keep pace with the critical measurement needs so far identified.

This factor of five is based principally on the measurement needs uncovered in *Measurements for Competitiveness in Electronics.*

The factor of five is a minimum because not all fields of technology critical to the products of the electronics and electrical-equipment industries have yet been studied, due to the huge sizes of these industry segments and the broad extent of their measurement needs. For example, in the electronics industry, assessments of the full scope of the measurement needs for the following product areas have not yet been developed and published: optical information storage; image generation (vision) systems for video; optical-fiber communications equipment and systems; and computer equipment and systems. (For both optical-fiber communications and computers, assessments have been completed and published at the materials and components levels, but not yet at the equipment and systems levels.) For the electrical-equipment industry, full assessments have not yet been developed and published for any area. EEEL is actively engaged in preparing the needed additional assessments, working again in collaboration with U.S. industry and other NIST Laboratories. EEEL's plans for such assessments are outlined in the section "Planning" on page 47.

COMPETITIVENESS DRIVING FORCES

This section of the plan examines the most fundamental forces that are driving the electronics and electrical-equipment industries. These forces derive principally from the pursuit of improved competitiveness and are introduced here in that context. They determine the nature of the response that EEEL makes in providing supporting technology to the industry. EEEL's responses are described at the strategic level in the two sections that follow this one.

The driving forces are best described in terms of the demands of buyers and the challenges that manufacturers face in meeting those demands. A brief summary of these demands and challenges is provided here. A full discussion is found in Chapter 1 of *Measurements for Competitiveness in Electronics.*

Buyers' Demands

Buyers, whether individuals or organizations, are demanding a greater diversity of services from electronic products in support of virtually every societal service in strategy (5) in Table 9 on page 11. Buyers are also demanding improved product characteristics, more attractive marketplace-exchange characteristics, and improved after-sales support. The principal factors of interest to buyers are outlined in Table 13.

In Table 13, and in the several tables that follow in this section, arrows mark the factors affected by the level of available measurement capability. That is, the factors marked are those for which manufacturers' measurement capability, or buyers' measurement capability, or both, are major factors in ultimately satisfying buyers and thus in realizing competitive positions for manufacturers. The presence of so many affected factors is the principal reason for the high leverage that measurement capability has on the competitiveness of products.[19]

Table 13: BUYERS' DEMANDS

Product Characteristics
→ performance
→ quality/reliability
→ compatibility

Marketplace Exchange
→ price
→ timely availability
→ agreement with manufacturer
→ specifications
→ proof of compliance

→ *cost of marketplace exchange*
→ *speed of marketplace exchange*

Support
→ installation
→ maintenance
→ daily operation

→ *cost of support*
→ *speed of support*

Table 14 expands on the first element in Table 13 by providing a short list of the most important buyers' demands for *product characteristics* for electronic and electrical products. In the simplest of terms, buyers want electronic products that handle more information, that offer decreased weight and size (often to enable increased portability), and that consume less energy. Classic examples of electronic products reflecting these buyers' demands are evolving laptop and handheld computers and emerging personal portable telephones, such as those associated with Personal Communications Services, which promise worldwide access. For electrical products, such as motors, increased energy efficiency is probably the single most important performance improvement desired by buyers, with decreased size and weight close behind.

Table 14: BUYERS' DEMANDS FOR PRODUCT CHARACTERISTICS

Performance
→ higher information capacity
→ higher information fidelity
→ higher information density
→ higher energy efficiency
→ decreased size and weight

Quality/Reliability
→ fewer defects on delivery
→ fewer failures during use

Compatibility
→ improved interfacing
→ reduced electromagnetic interference

Manufacturers' Challenges

To meet buyers' demands, manufacturers must address a wide range of challenges. These challenges are outlined in Table 15, Table 16, and Table 17. Table 15 focuses on the four fundamental steps that manufacturers must successfully address to realize competitive products in the marketplace. Table 16 and Table 17 expand upon some of the challenges implicit in those in Table 15 and meriting special mention. Specifically, Table 16 shows the challenges that manufacturers face in raising and protecting resources. Table 17 shows the challenges that manufacturers face in implementing new management strategies for improved competitiveness. Again, arrows mark the factors affected by the level of available measurement capability.

The role of measurements in Table 15 and Table 16 may be somewhat easier to understand than the role of measurements in Table 17. For Table 17, measurements provide *control* and *communication.* Measurements provide control that is critical for implementing new management strategies such as flexible manufacturing, which requires constant changes in manufacturing processes to produce a greater diversity of products. Product diversity is increasingly needed to compete on the basis of *economies of scope* rather than just the traditional *economies of scale.* Measurements provide communication in the sense that a high level of measurement capability, held in common by collaborating parties, is an important part of their language of communication. That shared capability is needed for effective communication *within* companies engaged in intensely collaborative tasks, such as total-quality management or concurrent engineering to accelerate product development. That shared capability is also needed for communication *among* companies conducting

Table 15: MANUFACTURERS' CHALLENGES - I

Research and Development
→ discovery
→ product design

→ *cost of R&D*
→ *speed of R&D*

Manufacturing
→ process design
→ process control

→ *cost of manufacturing*
→ *speed of manufacturing*

Marketplace Exchange
access
  export restrictions
  import restrictions
    tariff barriers
    non-tariff barriers
      nationalism
      local content
→ standards compliance
      many others
agreement with buyer
→ specifications
→ proof of compliance

→ *cost of marketplace exchange*
→ *speed of marketplace exchange*

Support
→ installation
→ operation
→ maintenance

→ *cost of support*
→ *speed of support*

cooperative development programs or serving each other as suppliers and customers.

EEEL responds to the driving forces for competitiveness by providing measurement support that affects virtually every measurement-dependent factor marked in the five tables. In addition, EEEL increasingly provides selected technology-development support for many of the same factors. The following two sections describe EEEL's response.

Table 16: MANUFACTURERS' CHALLENGES - II

Raise Resources
- capital
  - equity
  - debt
- labor
  - managers
  - workers
- matériel
  - → equipment
  - → supplies
- technology
  - supporting
    - → measurements
  - generic, other

Protect Resources
- intellectual property

Table 17: MANUFACTURERS' CHALLENGES - III

Implement New Management Strategies
- → total-quality management
- → flexible manufacturing
- collaboration outside
  - → cooperative development
  - → technology transfer
- collaboration within
  - → teamwork
  - → concurrent engineering

STRATEGIC DIRECTIONS ACROSS FIELDS

EEEL's strategic directions can be described in two ways: (1) those that are common across many fields of technology; and (2) those that are particularly important to individual fields of technology. This section looks at the former; they are outlined in Table 18. The next section looks at the latter.

The purpose of these two sections is to surface the most important factors driving EEEL's program and to characterize the most important aspects of EEEL's response. This characterization is based on a program consistent with the levels of resources assumed available in the section "Resource Assumptions" on page 13. Special attention is given here to predominant, new, or changing directions for EEEL's program.

Higher Accuracy and Sensitivity

Pursuit of higher accuracy and sensitivity in many measurements is a continuing priority for EEEL. Measurements referenced to *quantum phenomena* are especially important, since they rely on unvarying fundamental atomic constants, such as the electronic charge and Planck's constant. Higher absolute accuracy and higher sensitivity are particularly important for measurements used in basic research, where new phenomena might be missed entirely with any less capability. Higher absolute accuracy is increasingly important for delicate manufacturing processes, such as those used to make integrated circuits. The development and portability of processes to other manufacturing facilities require measurements of high absolute accuracy. More generally, industry efforts to achieve higher performance, improved quality control, and better technology transfer within companies and between companies in collaborative efforts are increasingly dependent on measurements of higher accuracy and sensitivity. Measurements are part of the language of collaboration.

More Measured Quantities

Industry wants measurement capability for an ever increasing number of measured quantities. This trend reflects the increasing complexity of electronic products, the materials from which they are made, and the processes used to make them. EEEL endeavors to respond, but cannot address all measured quantities requiring support, and thus must continue to set priorities carefully.

Higher Frequencies

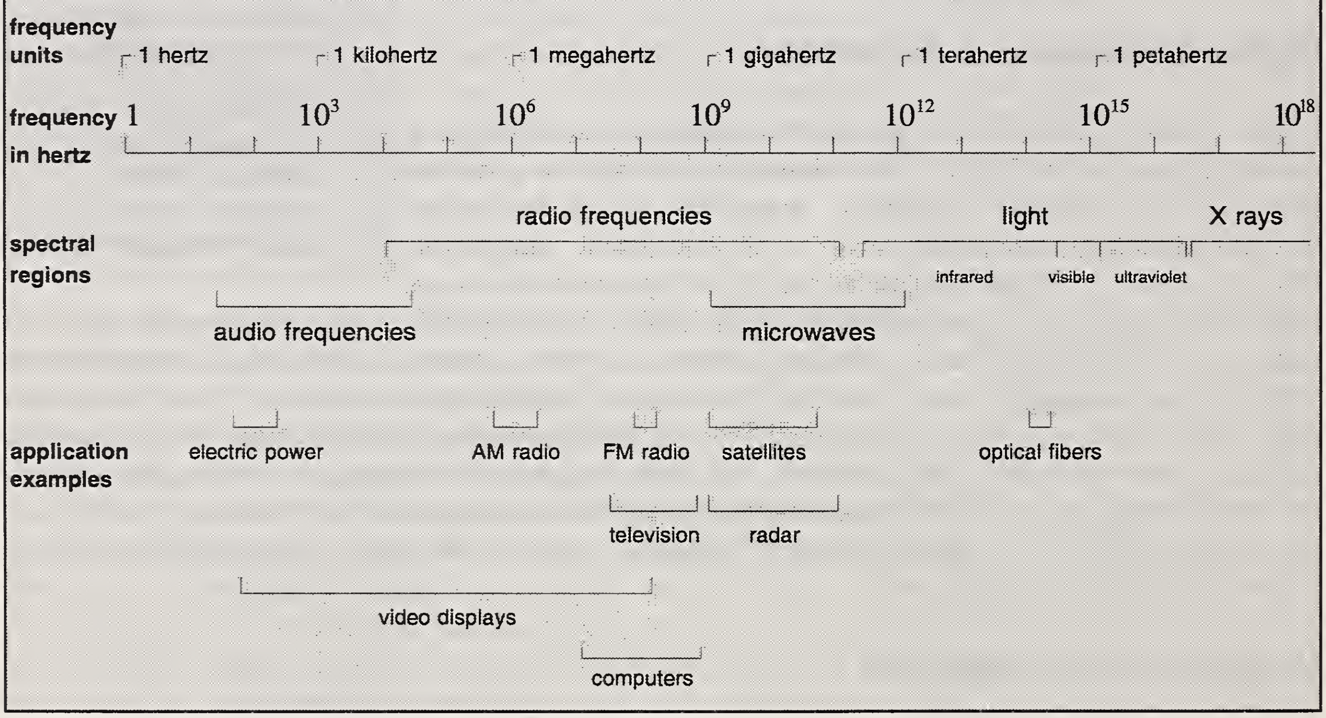
Table 18: STRATEGIC DIRECTIONS ACROSS FIELDS
Higher Accuracy and Sensitivity
More Measured Quantities
Higher Frequencies
Digital Techniques
Compatibility
Integration
Microdimensions
Materials Diversity
Systems Measurements
Measurement Efficiency
Manufacturing Measurements
Measurement Immediacy
Energy Efficiency
International Standards
Rapid Response

Measurement support for higher frequencies is increasingly important. Higher frequencies offer higher information capacity for communications and computing, higher resolution for radar, smaller antennas for all systems, including portable systems, and often improved immunity to interference.

Microwaves are the highest information capacity wireless technology available. They have frequencies from 1 gigahertz to 1000 gigahertz, as shown in Figure 1, but the most important part of the spectrum for most applications lies below 100 gigahertz. Microwave technology is integral to the success of new Personal Communications Services, intelligent vehicle/highway systems, ultra-fast computers, and video signal processing.

Lightwaves travelling in optical fibers are the highest information capacity cable technology available. These lightwaves have frequencies of 200 terahertz and are located in the infrared region just below the visible region. Optical fibers remain the core cable technology for the most sophisticated implementations of the National Information Infrastructure. Optical signal processing and optical computing are emerging areas with great promise.

Figure 1: OVERVIEW OF THE FREQUENCY SPECTRUM



Digital Techniques

Digital electronics continue to grow in importance, and so do supporting measurement requirements. While first prominent in computers, digital electronics have become increasingly important to measurement equipment, medical equipment, communications equipment, consumer electronics, and manufacturing systems broadly. Digital electronics are supportive of computational processes, such as the interpretation of sensor data. Digital electronics also enable maintaining signal quality in the presence of limited levels of degradation, which is especially critical in communications and computing systems. Digital techniques are employed at virtually all frequencies, extending from below one hertz to lightwave frequencies.

Compatibility

Compatibility in a variety of forms affects electronic and electrical products broadly. Two categories of compatibility are especially important: (1) electromagnetic compatibility, and (2) interface and interconnection compatibility. Each gives rise to a variety of measurement needs that EEEL is addressing.

Electromagnetic compatibility refers to the ability of electronic and electrical products to operate without mutual electromagnetic interference. With continued growth in the number of electronic devices, particularly those that must radiate to operate, such as portable telephones and wireless networks, special measurement methods will be needed for controlling both electromagnetic emissions and susceptibility to those emissions.

Interfaces and interconnections are everywhere in electronic and electrical products, and their performance is often the limiting factor in the overall performance of the products. Whether in optical-fiber communications systems or within integrated circuits, special measurement support is required for characterization and will continue to be a priority for EEEL's program. Measurement support for interfaces and interconnections is becoming very demanding as frequencies of operation rise and as multiple materials technologies are increasingly integrated into products. The higher frequencies lead to higher sensitivities of circuits to interface and interconnection characteristics. The multiple materials technologies employed give rise to difficult interfaces, such as optical-to-electronic interfaces and superconductor-to-semiconductor interfaces.

Integration

Measurement support for integrated circuits continues to be central. Integration remains the single most important manufacturing invention providing increased functionality per unit cost for electronic products. Integration also contributes to improved quality control and improved performance. For these reasons, success in advancing integration continues to be the single most important factor affecting marketplace competitiveness in a host of electronic technologies. Progress in the integration of silicon circuits at submicrowave frequencies has been integral to the success of those circuits for some time. Now progress in the integration of both silicon and compound-semiconductor circuits at microwave frequencies has emerged as a new important area. Integration of superconductor circuits has seen early progress, although significant markets for commercial products have not yet resulted. Integration of optoelectronic circuits is in the earliest of stages of development but will be a certain requirement for competitiveness. Integration of magnetic circuits, such as those being developed for magnetic recording, is also proving of increasing importance.

Microdimensions

Measurements of electromagnetic quantities on microdimensional scales are increasingly critical. In addition to the measurements made within integrated circuits, microdimensional measurements are needed to support fundamental advances made in magnetic and optical information storage. Optical approaches offer the possibility of three-dimensional information storage in the future, with unprecedented information capacities.

Materials Diversity

Measurements are increasingly required to support a greater diversity of electronic materials. Strategy (1) in Table 9 on page 11 illustrates the basic categories of these materials. The greatest expansion in diversity is taking place in the optical category, which includes optoelectronic, magneto-optic, and dielectric materials. Many of these materials are so different from each other that they give rise to entirely independent measurement problems. This materials diversity complicates greatly the measurement support that must be provided for optical applications, such as optical-fiber communications systems and flat-panel displays for advanced video systems.

Systems Measurements

Measurements are increasingly needed to support equipment and systems, and not just materials and components, in the sense outlined in strategy (3) in Table 9 on page 11. To date, EEEL has provided measurement support primarily for materials and components. There are several interrelated reasons for this emphasis. Measurement support for materials and components offers high leverage, since all of the equipment and systems built from them benefit. In contrast, measurements for equipment and systems are often peculiar to them and are thus not as broadly beneficial. Also, measurements for equipment and systems are often very difficult, and thus very costly, to develop. Optical-fiber communications systems provide an example of the difficulty of systems-level measurements. Special measurement challenges arise due to such factors as environment, access, longevity, spatial extent, temporal extent, complexity, and architecture; these complicating factors are described in *Measurements for Competitiveness in Electronics* on pages 286-289. In spite of these many difficulties, measurements for characterizing equipment and systems are clearly needed; and EEEL, as its resources increase, will be addressing more of them.

Measurement Efficiency

The cost of making measurements, entirely aside from their very significant impact on product realization, is a significant factor in U.S. competitiveness. For products made in integrated-circuit form, in particular, measurement costs can account for 20 percent of product costs. During early efforts to achieve integration in new materials, measurement costs can be even higher. For this reason, EEEL is constantly striving to reduce measurement costs. EEEL takes three principal approaches:

> Develop measurement methods that are inherently simpler to use, including those employing digital techniques amenable to automation.

Develop measurement methods, such as those relying on quantum phenomena, that are inherently simpler to support, because they either shorten the calibration chain or virtually eliminate it.

Reduce the number of measurements that must be made to characterize a product by providing strategies for identifying the critical measurements.

Manufacturing Measurements

Because of NIST's historical role as part of the Department of Commerce, measurement support for marketplace exchange has been, and will remain, a high priority for EEEL. Fortunately, measurements for the marketplace often also serve research and development, manufacturing, and after-sales support. However, in an increasing number of cases, particularly, as integration progresses, EEEL sees, and will act on, the need to develop measurement capability focused specifically on manufacturing.

Measurement Immediacy

The achievement of measurement immediacy, that is, of measurements that provide immediate feedback on the performance of a system, is a major emerging direction for measurement support and, therefore, will shape a significant part of EEEL's program.

The need for measurement immediacy arises principally in two environments: in manufacturing processes that must have real-time feedback to achieve active process control to enable making a product right the first time; and in installed systems that must be continuously monitored to assure their proper and reliable performance. Measurement methods that provide measurement immediacy must address a host of demanding challenges that vary somewhat with the application. Often included in those challenges are: non-interference with the processes or systems to be measured; small physical size; tolerance for hostile environments; stability over long periods of time; and very rapid response times.

Examples of areas of relevance for measurement immediacy in electronic and electrical products include: controlling semiconductor manufacturing processes, controlling electrical power systems, and monitoring performance in information networks. Electronic and optoelectronic techniques figure also in providing measurement immediacy for other products, such as physical structures. A key example is the use of embedded optical-fiber sensors to monitor aging and stresses in aircraft wings and building structures.

Achieving measurement immediacy is something like incorporating the electronic analog of the human nervous system into manufacturing processes, systems, and structures.

Energy Efficiency

Energy efficiency remains vital for environmental, economic, and convenience reasons. It is essential to the success of the exploding variety of wireless *portable and mobile* electronic products. For all of these reasons, EEEL will continue to pursue measurements focused on energy efficiency in electronic and electrical products based on a broad spectrum of electronic materials, including conducting, semiconducting, magnetic, and optoelectronic materials.

International Standards

Increasingly, EEEL's assistance is needed to support U.S. representation in growing international standards activities. This representation is necessary to provide a voice in standards that will affect the access of U.S. products to international markets. The U.S. Government, through the U.S. Department of State, selects U.S. representatives to international standards bodies that are the result of treaties with other nations. U.S. industry selects organizations to represent the United States in other international standards bodies. For example, U.S. industry selected the American National Standards Institute as the U.S. representative for the ISO 9000 standards being developed by the International Standards Organization.

The approach of other nations to standards differs somewhat from the approach of the United States. The United States relies primarily on voluntary standards developed by industry. The primary exception is standards of the U.S. Government, which are mandatory; they are often limited to products purchased by the Government. In contrast, other nations and groups of nations, such as the European Community, rely virtually exclusively on mandatory standards, like those in ISO 9000.

Lately, the role of the United States in international standards development has been seen by many in industry as needing strengthening. In particular, many in industry feel that additional Government support is needed. The Government's role is currently under examination at NIST, and EEEL's role will be affected by the outcome of this inquiry. To date, NIST has provided measurement capability and other technical assistance needed by participants in international-standards development. In a recent EEEL poll of industry interest, most industry representatives urged the expansion of this role to strengthen the hand of U.S. negotiators when standards are being set by international bodies. Industry representatives have made several specific suggestions. One suggestion is that the Government provide increased assistance in developing more cost-effective ways of accrediting laboratories that test to international standards, particularly the ISO 9000 standards. Another suggestion is that NIST participate directly in the international standards processes in some fields. A further suggestion is that the Government fund industry organizations directly to participate in international standards bodies. These ideas, and others, are the subject of NIST's current review.

Whatever the outcome of NIST's review, it is clear that EEEL will continue to experience an increasing demand from industry for consulting, training, and calibrations services designed to help industry meet the stringent requirements for measurement uniformity built into emerging international standards.

Rapid Response

Industry needs a more rapid response from NIST. Meeting industry's measurement needs with sufficient rapidity is one of the most difficult challenges that EEEL is facing. The total time to meet a measurement need is the sum of the time required to accomplish the several basic steps outlined in Table 19. The total time can vary greatly. Here are some examples, each representing a different part of the range of possible response times: (1) a

Table 19: IMPACT ON STEPS TOWARD RAPID RESPONSE

Steps	Increased Resources	Industry Roadmaps
identifying need	X	X
raising resources	X	X
developing solution	X	
delivering solution		X
achieving adoption of solution		X

few months to one year for an urgent measurement need which does not require considerable fundamental research and which can be addressed with existing financial and staff resources; (2) one to five years for the development of a documented calibration service; and (3) five to ten years for a major advance, such as a factor of ten improvement in accuracy, in a national electrical standard. Typically, benefits begin flowing to customers before the ends of these periods.

There are many factors that affect EEEL's ability to respond quickly. However, EEEL sees improvements coming from at least two developments, reflected in the right two columns in Table 19. The first development is the increased level of resources assumed in this plan. These resources, as shown in Table 12 on page Table 12, include more base funding, that is, more funding that EEEL can redirect. The second development is the emergence of industry roadmaps. These two developments primarily accelerate completion of the steps marked "X" in the table.

The roadmaps are developed by manufacturers of a specific product group to set directions and goals for a number of years into the future. The roadmaps may or may not spell out specific measurement requirements, but they improve EEEL's ability to anticipate measurement needs in either case. A major example is the roadmap being developed by the Semiconductor Industry Association for the manufacture of silicon integrated circuits.[20] It does spell out measurement requirements. A second example is the roadmap being developed by the Optoelectronics Industry Development Association for optoelectronics products.[21] In its present form, it does not spell out measurement requirements. EEEL supports the efforts of industry organizations to develop these roadmaps.

STRATEGIC DIRECTIONS WITHIN FIELDS

EEEL's strategic directions within individual fields of technology are described here. The fields are addressed in the order shown for EEEL's program structure in Table 10 on page 12.

Semiconductors

Table 20: SEMICONDUCTOR INDUSTRY GOALS

	1992	2007	Improvement
feature size (μm)	0.5	0.1	5
speed on chip (MHz)	120	1000	8
defect density (/cm^2)	0.1	0.002	50
memory size (Mbytes)	16	16,000	1000

The challenges that U.S. semiconductor manufacturers must meet to remain competitive are daunting. They include virtually all of the challenges presented in broad terms in the section "Competitiveness Driving Forces", beginning on page 15. In short, U.S. semiconductor manufacturers must offer greater functionality and performance for more diverse applications at lower costs. To accomplish these aims, manufacturers are pursuing specific goals, like those in Table 20, developed by the Semiconductor Industry Association as part of its roadmap.[22] They include feature sizes 5 times smaller, speeds 8 times faster, defect densities 50 times smaller, and memory capacities 1000 times greater (for dynamic random access memories). In pursuit of these goals, the industry must address a host of important technical challenges. Four that are vitally important to the industry *and* that require considerable expansion in NIST's program have been selected for discussion below. A fifth area, lithography, is also vitally important to the industry and can be addressed with more evolutionary changes in NIST's program. EEEL's response is part of an EEEL-managed NIST-wide program in support of the semiconductor industry, thus the mention of NIST and EEEL alternately below. The key focus of this program is measurement support for improved manufacturing processes.

Industry is encouraging the expansion of this program through formation of a National Semiconductor Metrology Program at NIST. It would be funded at a level of $25 million per year and would focus on measurement support for silicon CMOS digital integrated circuits. The establishment of this expanded program is assumed successful here. In addition, EEEL will maintain a smaller program that focuses on power semiconductors, compound semiconductors for both electronic and optoelectronic applications, and analog devices.

Modeling for Product and Processing Design

Table 21: MODELING
Product
device
circuit
Processing
process
equipment
factory

Semiconductor integrated circuits have become so complex that remaining trial-and-error methods used for their design and manufacture are too ineffective and must be eliminated. Efficient and successful designs require an increasing number of mathematical models embodying the underlying physics, as outlined in Table 21. The models guide development by enabling testing through simulation rather than through production of expensive prototypes. To date, *device models* have been employed to support the design of the individual devices (transistors) within integrated circuits. Similarly, *process models* have been used to support the design of individual manufacturing processes. These models require major improvements. In addition, new types of models are needed. As operating speeds increase, circuit elements interact more intimately, giving rise to the need for *circuit models* to guide circuit design. *Equipment models* are increasingly needed to enable design of complex manufacturing equipment to implement processes. Finally, *factory models* are needed to provide efficient overall management of manufacturing equipment. Models help achieve the control required to perform correctly all of the 300 to 500 steps needed to produce working modern integrated circuits.

Model development will be conducted primarily in universities and industry. NIST, including EEEL, will provide measurement methods for, and reference data on, materials properties, chemical reaction rates, and other factors needed as input for the models. EEEL will also develop test methods that industry will use to evaluate model performance by comparing process output with model predictions.

Measurement Immediacy During Processing

Table 22: MEASUREMENT IMMEDIACY
off line
in line
in situ
real time

Closely related to the need for better process models is the need for measurements more immediate to the manufacturing processes used to make integrated circuits. The steps toward increasing immediacy are shown in Table 22 from top to bottom. At present, industry uses a large number of *off-line* measurements (made off the processing line) to check process performance. Industry also uses a somewhat smaller number of *in-line* measurements (made between processes but still outside processing equipment). Both of these types of measurements interrupt processing. For efficiency, industry would prefer measurements made *in situ* (made inside processing equipment but after process completion), which are less disruptive. However, all three of these measurement approaches lead to discarded product when processes go wrong. Ideally, industry would like *real-time* measurements. They are made inside processing equipment, during processing, and in time to control processes so they work right the first time.

The measurement methods needed to provide improved immediacy must address difficult challenges, outlined in Table 23. Initially, EEEL's strategy will be to develop new measurement methods and supporting theory responsive to the first three challenges, but adaptable to the last two. This initial focus is necessary to reduce the number of quantities for which there are currently no adequate measurement methods, even for off-line and in-line environments. A special emphasis will be placed on non-contacting methods, such as optical methods, that offer the best prospect for subsequent adaption to in-situ and real-time environments. As NIST's resources increase during the planning period, NIST and EEEL will broaden the spectrum of measured quantities addressed to include nearly the full scope of quantities requiring NIST's assistance. This effort will extend support to in-situ and real-time environments, including those presenting the difficult last two challenges in Table 23.

Table 23: IMMEDIACY CHALLENGES
more measured quantities
new measurement techniques
higher accuracy levels
miniaturized measurement systems
hostile measurement environments

Contamination During Processing

Contaminants are an anathema to integrated circuits because of the circuits' small feature sizes and sensitive electrical properties. Contaminants are sourced in the solid, liquid, and gaseous starting materials used for manufacturing, in the air in manufacturing facilities, and in the wear by-products, and other unintended by-products, of processing. Contaminant levels as low as 1 part in 10^{13} in starting materials, and particle counts as low as 4 per cubic meter[23] of air, can be troublesome.

Table 24: SOURCES OF CONTAMINATION
starting materials
gaseous
liquid
solid
ambient air
processing by-products

Present measurement capability for detecting and identifying contaminants is inadequate to permit desired levels of control. For starting materials, NIST will develop both improved measurement methods and new standard reference materials for assuring the accuracy of the methods. EEEL, in particular, will focus on contaminants in bulk silicon. EEEL will mine out existing methods by establishing their lower limits of sensitivity. EEEL will focus on non-destructive methods that offer high accuracy, high selectivity (often optical), and susceptibility to miniaturization. For particle contamination, NIST will explore the possibility of entirely new measurement approaches since desired particle levels are below practical extrapolations from known methods.

Packaging

Completed chips must be placed in "packages" that provide physical protection, heat dissipation, and electrical interconnections. As chips have become faster and more complex, package design has become more complex, too. Power levels have risen, pin counts have increased to the hundreds, and lead layout has become critical. In fact, packaging costs are comparable to chip costs.

Table 25: PACKAGE PROPERTIES
electrical
mechanical
thermal
chemical
molding/fluidic

NIST's approach will be to provide reference materials data on critical categories of properties, like those in Table 25, that industry can use in designing its packages. When current measurement methods for generating needed data are lacking, NIST will develop new methods. NIST will provide reference data for electrical properties of package materials. EEEL will also provide measurement methods that manufacturers and users of packages can employ to verify package performance.

Magnetics

The services provided by magnetic technology span broad dimensional ranges and diverse applications, ranging from microscopic bits of stored digital information in electronic products to huge cores for power-system transformers. The rich diversity of magnetic phenomena and potential applications has been barely tapped and continues to demand more from supporting measurement technology.

Information Storage

The single most important driving force in magnetic information storage is the push to smaller sizes for magnetically stored bits of information. These smaller sizes are necessary to achieve higher areal densities of information on magnetic surfaces, such as those on hard disks, floppy disks, and magnetic tapes. Closely coupled to capacity is the push to higher rates of data transfer. Industry's goal is to achieve massive storage capacities at affordable costs.

The progress that industry has made to date has been remarkable; the progress that it must continue to make to remain competitive is also remarkable. The current state of the art in data transfer rates from magnetic storage media is far too slow to take full advantage of the speeds of the electronic components in computers. Similarly, the current state of the art in capacity is too low, and the cost per unit capacity is too high, for demanding applications such as high-definition television.

In response EEEL has chosen, as the predominant direction of its magnetics program, to expand its efforts in support of industrial research and development toward new magnetic recording technologies that offer remarkable improvements in storage capacity and speed. This support takes the form of both measurement development and technology development. EEEL is developing techniques for measuring and mapping magnetic effects on scales below 1 micrometer and down to 10 nanometers, employing scanned-probe techniques. These techniques can be used to image both magnetic media and magnetic recording heads. EEEL is also employing those techniques to conduct fundamental research on microscopic magnetic phenomena with scales so small that size and quantum effects predominate. The goal is to provide characterizations of magnetic materials and magnetic structures that address both theoretical and practical factors of use to industry in pursuing fundamental advances in performance. EEEL is also developing technology for improved resolution in magnetic and magneto-optical storage systems. One new approach employs an optical-fiber technique and is described in the section "Optical Information Storage" on page 35.

Magnetic Sensing

EEEL's contributions to magnetic-sensing applications derive principally from its focus on methods for supporting magnetic information storage. Much of the same measurement technology will prove useful for research and development in other fields, such as superconductivity. The same technology will also prove useful for development of magnetic sensors for manufacturing equipment and for other products as different from each other as automobiles and medical equipment.

Power Materials

EEEL recognizes an important need for improved measurement support for magnetic materials for applications in electrical equipment. Two of the most important materials are so-called soft magnetic materials for lower loss transformer cores and strong permanent magnets for more efficient motors. However, measurement development in support of these materials is beyond the level of resources assumed available here.

Superconductors

EEEL serves industry segments that produce superconductor products. EEEL also employs superconductors to serve other industry segments whose products are based predominantly on other technologies. In particular, EEEL uses superconductors to provide national electrical standards. EEEL's efforts are part of a broader NIST program on superconductivity.

Table 26: SUPERCONDUCTOR CHALLENGES AND CAPABILITIES

Challenges
- complex materials to understand
- complex fabrication processes
- cryogenic cooling requirements

Capabilities
- enormous current capacity
- high energy efficiency
- ultra-high speeds
- ultra-high sensitivity
- ultra-high accuracy
- small sizes

Superconductors have begun to penetrate commercial markets for electrical applications and for electronic instrumentation. The largest market has been for superconductor electromagnets, with worldwide sales between one and two hundred million dollars per year.[24] They are used principally in magnetic-resonance-imaging equipment and in laboratory research apparatus. Ultra-sensitive superconductor laboratory instruments, such as magnetometers and voltage standards, are increasingly widely used. These applications require the unique properties of superconductors.

Achieving broader commercial success for superconductor products will require addressing several challenges, as outlined in Table 26. However, remarkable progress is being made. This progress is driven by demand for the unparalleled capabilities of superconductors, which are truly an ultimate technology. Even the fundamental limitation of cryogenic cooling is increasingly viewed as less important, principally because of three developments: the emergence of high-temperature superconductors which are easier to cool; the rapid development of small closed-cycle refrigerators which free users from the need for consumable cryogenic liquids; and the realization that other technologies, such as semiconductors, will also require cooling to reach their ultimate limits in both speed and low electronic noise.

Electrical Applications

Most present and prospective electrical applications of superconductors rely on forming coils of superconductor wire to create superconductor electromagnets that provide high magnetic fields. Important electrical applications are shown in Table 27. All require electromagnets except electric-power transmission, for which underground superconductor lines remain a possibility. For all of these applications, industry's principal goal is achieving high values of current-carrying capacity under realistic operating conditions.

Table 27: ELECTRICAL APPLICATIONS OF SUPERCONDUCTORS

- electromagnets for research
  - general purpose
  - accelerators
  - fusion energy
- motors
- generators
- magnetic levitation
- magnetic energy storage
- transmission lines

To help, EEEL provides a diversity of services, including: measurement capability for critical quantities, such as current-carrying capacity; fundamental research on degradation in current-carrying capacity from mechanical, thermal, and processing effects; materials reference data on normal metals employed in superconductor wires and on non-metallic materials used in magnet structures; leadership in international standards activities for both terminology and measurement methods; and round-robin measurement intercomparisons to assure the accuracy of important measurements. Particularly critical is EEEL's measurement support for the high-field magnets used in the international effort to develop fusion energy, which focuses principally on low-temperature superconductors. For high-temperature superconductors, EEEL has been providing measurement capability for realizing practical wires and tapes. With attractive current-carrying capacities now emerging for these new materials, EEEL is redirecting part of this effort to providing measurement support for the next phase of development: the realization of practical coils made from the wires and tapes. In particular, EEEL will provide measurement capability for, and fundamental research on, sources of degradation in the current-carrying capacity of coils. Those sources of degradation include stress fatigue, field direction, and alternating-current effects.

Electronic Applications

While electrical applications of superconductors exploit principally the first two capabilities in Table 26, electronic applications exploit them all. Electronic devices made from superconductors are diverse. Realization of these devices in integrated-circuit form is often necessary for implementing them at all and is always critical to their future commercial success. EEEL's program in superconductor electronics responds with two major efforts: support for achieving integration; and development of integrated superconductor devices for measurement and information applications.

To support integration, EEEL has developed one of the world's leading laboratories for fabricating superconductor integrated circuits. EEEL continues to develop low-temperature superconductor electronics, but its long-range focus has turned to high-temperature superconductors, since much of the future of superconductor devices lies with them. Worldwide, impressive progress has been made with these difficult high-temperature materials; and initial superconductor integrated circuits have been demonstrated, with unique contributions from EEEL. Nevertheless, formidable challenges remain in several areas: growing thin films of superconductors and insulators by epitaxial (layer-by-layer) methods; understanding interface properties between thin films; and controlling those properties during processing. EEEL is developing measurement methods and materials knowledge needed to resolve these problems. EEEL is also developing methods for measuring the minute microwave-frequency losses in superconductor films to support the future introduction of low-loss superconductor microwave components.

To support device development, EEEL is addressing the broad spectrum of applications shown in Table 28. The dc voltage standard developed by EEEL is the most prominent output. EEEL is adapting the technology in this dc voltage standard to provide an ac voltage standard. The application of superconductor technology to such standards is addressed in the section "National Electrical Standards" on page 44. Nearly all applications in Table 28 are the subject of present or upcoming efforts. The exceptions are signal-detection devices for deep-space listening and magnetic-field measurement devices (superconducting quantum interference devices); these have been addressed in earlier work.

In developing devices, EEEL is pursuing two principal aims: high performance levels, and broad accessibility to those performance levels for multiple users. Examples of the pursuit of high-performance levels are found in present and upcoming work on ac-voltage and dc-current standards, non-ionizing radiation measurements (particularly infrared), and ac-to-dc conversion devices to support accurate ac measurements. EEEL is pursuing broad accessibility through three principal approaches. The first approach is to provide measurement standards that, like the voltage standard, are as close to intrinsically accurate as possible. This approach fosters exporting the standards directly to users so that they acquire the same level of capability that NIST has, which is impossible to achieve with any calibration chain, even an elaborate and costly one. The second approach is to move steadily from low-temperature to high-temperature superconductors to ease cooling requirements. The third approach is to implement these devices in integrated-circuit form, not just to facilitate development, but also to enable future commercial manufacture at costs attractive to the marketplace.

Table 28: ELECTRONIC APPLICATIONS OF SUPERCONDUCTORS

Measurements and Standards	Preeminent Capability
voltage (dc and ac)	accuracy
magnetic fields (dc)	sensitivity
ac-to-dc conversion	accuracy
non-ionizing radiation	sensitivity
ionizing radiation	sensitivity
Information Applications	
generation	
millimeter-wave signal source	speed
manipulation	
analog-to-digital conversion	speed
signal detection	sensitivity
terahertz mixing	speed
amplification	sensitivity
transfer	
interconnecting lines	speed

Low Frequency

Low-frequency products are defined here as those operating anywhere within a very broad frequency range, extending from zero frequency (direct current) up to 1 gigahertz, which is the beginning of the microwave range covered in the next section. An examination of Table 7 on page 9, shows how varied and economically significant these products are. They include a diversity of electronic components and many types of equipment, such as telephone and telegraph equipment used in the local loop; AM, FM, and TV broadcast and cable communications equipment; computers; industrial electronics; electromedical equipment; and consumer electronic products. Low-frequency industrial electronics equipment, including a variety of measurement (test) and control equipment, plays an especially critical role; such equipment is used in the development and manufacturing of virtually all electronic products and many other types of products as well. Further, all of the electrical products in Table 8 on page 10 operate in this frequency range.

At the assumed level of resources, EEEL cannot launch a program of measurement support specifically targeted at each of these product areas. Instead, EEEL provides support in fundamental forms that benefit every one of these product areas in major ways. Through the work described in this section, EEEL supports measurement of the values of passive components, such as resistors, capacitors, and inductors. EEEL also provides methods for characterizing active components, such as integrated circuits, and circuit assemblies, but with a special focus on those products used for measurement. This work complements that in the section "Semiconductors", which focuses principally on measurements for the development and manufacturing of integrated circuits.

Because of the critical role of low-frequency measurement and control equipment, EEEL extends measurement support to the equipment level for these products. That is, EEEL provides measurement methods that address the overall performance of this type of equipment, not just the performance of the components or circuit assemblies inside.

In providing this support, EEEL pursues two key directions: achieving higher accuracies at higher frequencies for evaluation of components, circuit assemblies, and equipment; and advancing measurement efficiency.

Higher Accuracies at Higher Frequencies

EEEL's pursuit of higher accuracies begins with improving the interface between ac measurements and dc measurements. The standards that underpin accurate dc measurements are described in the section "National Electrical Standards" on page 44. As explained there, ac measurements of important electrical quantities are verified in comparison with dc measurements. To improve this interface, EEEL is developing, in collaboration with industry, a new ac-to-dc comparison device that is implemented as an integrated circuit. It will provide higher accuracy, and it will be more easily replicated for wider use. A second approach, employing superconductors, is also under development and promises even higher levels of accuracy. In a third approach, EEEL has developed digital sampling and synthesis techniques that are providing superior accuracy at frequencies below 1 kilohertz and above 1 megahertz and that interface readily with automated systems.

To achieve higher levels of accuracy at higher frequencies, EEEL is developing new measurement methods, and in some cases new measurement reference standards, to support measurement of such fundamental quantities as ac voltage, current, resistance, capacitance, and inductance at frequencies up to 100 kilohertz. EEEL is also endeavoring to exploit digital techniques to provide versatile and accurate methods for measuring ac voltages and currents at frequencies up to 500 megahertz. Finally, EEEL is extending its measurement support for pulse characteristics from the low end of the low-frequency area up to, and into, the microwave area above 1 gigahertz. Measurement of pulse characteristics is increasingly important to digital systems as operating speeds increase.

These several new forms of measurement capability will be used as the basis for improved calibration services from EEEL.

Measurement Efficiency

As electronic components and equipment have matured, they have become very complex. This complexity has greatly increased the cost of testing to assure proper performance. This problem afflicts analog circuits, digital circuits, and so-called mixed-signal circuits that employ both analog and digital circuits. In fact, for some mixed-signal integrated circuits, testing costs can account for 20 to 50 percent of sales price. For some complex electronic products, full testing of every possible internal state is either technically impossible or economically prohibitive. The solutions to this problem will not come easily and will require new thinking.

To help, EEEL is focusing first on analog and mixed-signal circuits since they are the most critical to measurement equipment. EEEL will help manufacturers reduce the number of measurements or tests required to characterize and calibrate these products. EEEL's support will take the form of modeling approaches that manufacturers can use to develop product-specific models. These models will help them identify smaller sets of measurements needed to achieve desired levels of characterization. EEEL will endeavor to provide this information in the form of software tools that are readily accessible to manufacturers and users. In addition, EEEL will pursue development of theoretical bases for fundamental advances in the self-calibration systems that are being built right into electronic measurement equipment.

For digital circuits, EEEL is evaluating the need for improved methods for locating and diagnosing circuit faults, including so-called built-in test methods. This subject is an important part of EEEL's current study of the measurement needs of computer manufacturers, as discussed in the section "Computers" on page 36. EEEL's directions in this area will be determined by the outcome of that study. At present EEEL is not addressing this area. In addition, EEEL recognizes that, before entering, it would have to identify fundamental contributions that are capable of leveraging industry's considerable efforts in this area and that are within reach of EEEL's resources.

Microwaves

For years, microwave equipment has represented a very large share of the U.S. electronics market, but applications have been limited principally to those for which the high cost of this technology could be borne. Those applications include defense systems and major systems supported principally by Governments or large corporations: satellite communications, airport communications and radar, corporate by-pass communications, weather radar, etc. Penetration of microwave technology into broader commercial applications and into the consumer market has been limited to a relatively small number of product types.

Now the special capabilities of the microwave frequencies are deemed essential to achieve increased information capacity and smaller antennas for communications systems, higher data processing speeds for computers, faster signal-processing circuits for advanced video systems, and new radar systems for intelligent vehicles and highways that support such functions as collision avoidance and traffic-light control. Not widely understood is the fact that computers, with digital clock rates just now surpassing 100 megahertz, are now evidencing microwave behavior and must be designed from here on with microwave technology if they are to operate faster.

In the face of such giant potential markets, U.S. industry is struggling to make microwave technology more affordable. The U.S. Government, through the Federal Communications Commission, has encouraged industry's efforts to achieve broader markets for microwave products by reassigning microwave frequencies in the area of 2 gigahertz for use by new Personal Communications Services. Additional spectrum may be made available in the future. These services contemplate worldwide communications access from portable handheld telephones and other communicating devices. The international race for broad commercialization of microwave technology is on, and the principal vehicle for reducing costs is the implementation of microwave integrated circuits.

Integration

In response, EEEL has steadily refocused its program from measurement support for individual components (or discrete components) to measurement support for integrated circuits. Such support will require new measurement methods and reference standards useful for measurements in the tight confines of microwave integrated circuits. These measurement methods must be capable of operating at extraordinarily high frequencies without interfering excessively with normal circuit operation. Central to EEEL's program is an emphasis on measurement support for characterizing interconnections, both within integrated circuits and among them, especially in packages containing so-called multi-chip modules. Interconnections are invariably a limiting factor in system performance.

Measurement Efficiency

A second major direction for EEEL is measurement efficiency. Because microwave measurements are expensive, they add significantly to the costs of developing and manufacturing microwave integrated circuits. New measurement methods and reference standards can help. As a key example, EEEL will develop new passive measurement reference standards that can simplify the calibration of network analyzers used for measuring both active and passive microwave circuits.

EEEL's efforts at cost reduction extend to antenna measurements, also. Particularly important are measurements for sophisticated phased-array antennas that offer high-speed electronic control of beam direction and shape. These antennas will serve in greater quantities in applications such as Personal Communications Services that will employ potentially hundreds of low-flying satellites. The key need is to supplement the present scanned approach to antenna measurements with faster methods that still yield acceptable levels of accuracy. The new methods may approximate "photographing" the desired field patterns.

Lasers

Lasers continue their march from the laboratory to practical applications, serving both energy and information functions, with the latter accounting for a slightly larger market share in 1993. In the energy category, the greatest dollar value of lasers worldwide is consumed by materials-processing and medical applications, in that order. In the information category, optical-fiber communications and optical information storage dominate in consumption of lasers among eight major applications. Lasers continue to be the single most important component for optical information applications generally.

Changes in the relative consumption of different types of lasers continue. In 1993, for the first time, semiconductor diode lasers surpassed the long-time market leader, carbon-dioxide lasers, in dollar value of sales.[25] In part, this development reflects the relative growth in information applications, which diode lasers serve so well. But also, this development reflects the expanding capabilities of diode lasers which are operating at ever higher power levels and at more wavelengths.

Laser manufacturers need a broad spectrum of measurement support for both lasers and laser optics. EEEL's present program of measurement support for lasers is very small and is thus focused on a very limited number of the highest priority needs. Specifically, EEEL's major focus is on the development of beam energy and power measurements which are required to support virtually all applications and are vitally important to the safe use of lasers. Key emphases are on improving accuracy and on widening the wavelength ranges and the power and energy levels supported, in response to expanding industry needs. During the planning period, EEEL will add a relatively high level of support for spatial beam-profile measurements. They represent one of seven categories of beam-quality measurements that are critically needed for both energy and information applications. EEEL will also provide a limited amount of support for some measured quantities that fall in a second category: temporal beam-quality measurements. They are especially important for information applications and the diode lasers that serve them. However, it appears unlikely that EEEL will be able to provide measurement support for the five remaining categories of laser measurement needs at the assumed level of resources. Also, it appears unlikely that EEEL will be able to address any of eight major categories of laser-optics measurement needs.

Optical-Fiber Communications

Optical-fiber communications are the highest information-capacity cable technology available for communications systems. They will be central to the realization of the high-performance tasks contemplated for the National Information Infrastructure. They are one of several optoelectronics applications addressed by the roadmap being developed by the Optoelectronics Industry Development Association.[26] Optical-fiber communications systems are evolving in several specific directions described below, and those directions are driving the need for supporting measurement capability.

Higher Information Capacity

The highest data rate employed in today's installed optical fiber systems is 1.7 gigabits per second. This is only about one one-thousandth of the estimated practical capacity of an optical fiber. Realizing higher levels of capacity will enable optical fibers to provide greatly expanded services for capacity hungry applications such as high-definition television. More generally, on-demand video services require enormous information capacity to serve multiple customers in a networked environment. On-demand video permits customers to request video programs of their choice, at the time of their choice.

The limitation to achieving higher information capacity lies in the transmitting and receiving components used with the fibers, rather than in the fibers themselves. These components create light, place information on it, and remove information from it at the receiving end. The two principal means of increasing capacity are to employ multiple closely spaced wavelengths and to increase the data rate on each of the wavelengths. EEEL is helping by developing measurements that support both means. Included will be new measurement methods and measurement reference standards for measuring wavelengths and for determining the performance of transmitting and receiving systems operating at tens of gigahertz.

Long Transmission Lengths

Maintaining high information capacity over long distance lines is particularly important and poses several challenges. To compensate for attenuation in the strength of lightwaves passing through optical fibers, the industry is developing optical amplifiers. When placed periodically along a fiber line, they renew the strength of a lightwave without the need for conversion to electrical form and back to optical form, as in earlier techniques. They also can handle the multiple wavelengths and high data rates per wavelength required for high information capacity. Unfortunately, at the higher data rates, the characteristics of the fibers cause digital light pulses to spread out, or disperse, somewhat.

EEEL is helping industry by developing measurement methods needed for developing optical amplifiers and for characterizing the various forms of dispersive degradation. EEEL is also assisting in the development of the technology for new optical amplifiers through Cooperative Research and Development Agreements with industry.

Fiber to Customers (Local Loop)

To date, most optical fibers have been installed in cross-country and undersea lines. Relatively little fiber has been run from these lines directly to the homes and businesses of individual customers through the local loop. Such connections will be needed if customers are to gain access to services requiring the highest information capacity. Creation of the local loop is an enormous investment for those installing the services. Enormous numbers of connectors and couplers (splitters and combiners) are required. They must exhibit very low losses in light strength to minimize degradation of the signal. The local loop will also require large numbers of switches to redirect lightwaves from one circuit to another to support the local loop.

EEEL is focusing a considerable effort on measurement support for further reductions in light losses within connectors, with a special emphasis on accurate measurements of the geometry of connectors and fibers. EEEL is also developing measurement support for characterizing the optical properties of the materials most important to switching, with a special focus on the non-linear properties that are the basis for most switching mechanisms.

Integrated Optics

Most components for optical-fiber communications systems are still made in individual (discrete) forms. To reduce costs and remain competitive, manufacturers will increasingly have to implement components in integrated-circuit form. During the planning period, EEEL anticipates an increasing level of effort to support integration.

Initially, this support will focus on measurements supporting the development of components in integrated form (as opposed to measurements supporting manufacturing process control). Among the supported devices will be integrated-optic lasers (the key component in transmitters), detectors (the key component in receivers), and amplifiers. EEEL will also work collaboratively with industry on the evaluation of new types of materials with potential for use in these devices.

While this work proceeds, EEEL will be surveying industry's needs for measurements to support manufacturing process control. These needs are evolving quickly at this early stage because the materials technologies that will eventually dominate integrated optics are not yet clear. Integrated optics are complicated. A key reason is the remarkable breadth of materials that they must employ to achieve the diversity of effects required. At the assumed level of resources, EEEL will undertake only limited development of process-control measurements, not the comprehensive assault required by any integrated-circuit technology. Based on its survey, EEEL will select a high-impact area for attention. A candidate is in-situ measurement for layer-thickness control during processing.

Systems Measurements

Systems-level measurements for determining the overall performance of optical-fiber communications systems and for finding faults in them are a complex subject. As noted above, the nature of the challenges that arise at the systems level have been described in *Measurements for Competitiveness in Electronics* on pages 286-289. Within the assumed level of resources, EEEL will not be able address the measurement needs of systems on a comprehensive level. However, EEEL will be able to provide increased support for at least one paramount need: the development of higher resolution methods for fault detection through optical time-domain reflectometry. This optical radar technique transmits light down a fiber and examines the reflections to find a host of types of defects, such as kinks or weak connections in the fibers. This type of fault detection will be central to the implementation of the local loop. The loop's multiplicity of paths and components will require a multitude of measurements to assure their correct functioning.

Optical-Fiber Sensors

Optical-fiber sensors offer attractive physical characteristics, such as small size and weight, good environmental tolerance, extraordinarily high information capacity, and remarkable capabilities for distributed sensing (all along the length of the fiber). Optical-fiber sensors have found their way into markets for a diversity of measurement applications for displacement, rotation, temperature, flow, pressure, fluid level, chemical and biochemical quantities, and magnetic and electrical quantities. For some applications, such as sensing pressure within the human body or sensing rotation (in gyroscopes) for new commercial aircraft, they are something of a minor revolution. In fact, optical-fiber gyroscopes are now available for automobiles in Japan.

Despite this success, the large potential markets for optical-fiber sensors have not yet been realized. Two reasons seem especially important: (1) costs for the sensors are high, and without adequate sales volume, the development of more efficient manufacturing processes to lower costs is not occurring; (2) selectivity, and sometimes accuracy, remain challenges for the sensors. Selectivity is the ability of a sensor to measure a single quantity of interest without responding to changes in other quantities. Ironically, the problem with selectivity arises from one of the virtues of optical-fiber sensors: they can measure almost anything. Industry is responding to the cost challenge by attempting to exploit the diverse measurement capabilities of the sensors. If sensors can be developed that employ a similar mechanism to measure multiple parameters, then sufficient market size may result to justify the manufacturing process development required to drive costs down.

EEEL is supporting industry's efforts by developing measurement methods and standards for the various components used in sensors. For example, EEEL is working with the Optical Fiber Sensor Committee of the Telecommunications Industry Association to establish standard methods of measuring the polarization properties of high-birefringence optical fibers, which are a critical component of optical-fiber gyroscopes. Also, EEEL is working with the Navy and a group of companies to develop a standard quarter-wave plate, which is an essential element in the measurement process in many optical-fiber sensors.

EEEL is also developing next-generation sensing technology. A large part of this work is focused on sensors for measuring electromagnetic quantities. For all measured quantities, an important emphasis of this work is minimizing the response of the sensors to extraneous effects, especially vibration or changes in temperature. EEEL will address the problem of sensor selectivity by evaluating sensor mechanisms that appear particularly promising for improving selectivity. EEEL will address the problem of limited market size for a particular type of sensor by evaluating sensor mechanisms that employ similar technology to measure several different quantities and thus offer economies in manufacturing. Low-coherence interferometry is a good example of a such a technology; it also offers better selectivity than many other mechanisms.

Optical Information Storage

The technologies of optical information storage and magnetic information storage are both pushing to new highs in performance. Both offer ever increasing areal storage densities. Optical systems offer high-capacity media in the form of optical disks that are removable. Magnetic systems offer faster access and read/write times.

At the assumed level of resources, EEEL will not be able to launch a major program of measurement support for the very important field of optical information storage. However, EEEL will endeavor to meet some of the key metrology needs with extensions of the measurement capability that it is developing for other areas. For example, selected methods for characterizing read/write optical media, which are based on magneto-optical techniques, will be provided as an outgrowth of EEEL's work in support of magnetic media. Similarly, measurement support for characterizing the short-wavelength lasers needed to reach higher areal information densities in emerging systems will be provided as an extension of EEEL's work on lasers. Finally, EEEL will pursue a technology-development effort that may yield a technique for significantly reducing optical spot size in order to increase areal information density in magneto-optical storage systems. The technique is based on the near-field behavior of an optical-fiber and is closely related to EEEL's development of a measurement technique called scanned near-field optical microscopy. This project exemplifies the close connection between advances in measurement capability and advances in technology more generally.

Optical Signal Processing and Computing

Optical technology holds the promise of powerful new capabilities for signal processing and computing. Among these promises are powerful "parallel" computing techniques that literally compute all parts of a solution simultaneously, instead of serially as in electronic computers. The power of this technology has been demonstrated in optical apparatus for performing instantaneous Fourier transformations.

These optical technologies are in the earliest stages of development; and EEEL cannot justify at this time a major program, despite the technical excitement of the area. Rather, EEEL's strategy will be to support those elements of this technology that are showing promise for earliest use when integrated into electronic computers. EEEL thinks of this as "optics in computing". EEEL will give special emphasis to measurement support for optical interconnections within computers, including interconnections employing optical fibers and free-space techniques such as those employing steerable arrays of light sources. Such interconnections promise immunity to interference and fast rates of data transfer among internal computer components. They may facilitate major progress in parallel computing techniques in electronic computers. They hold promise for breaking the present interconnection barrier to faster computer performance.

More generally, EEEL sees many of the capabilities of its present programs in optical-fiber communications providing benefits for optics in computing and for optical signal processing and optical computing. Movement into the new areas will be a natural extension of EEEL's current efforts, when resources permit and when technical progress merits.

Computers

EEEL currently supports computers by providing measurement support for other fields of technology, as shown in Table 29. This support is provided for materials, components, including integrated circuits (ICs), and equipment. However, EEEL recognizes that industry may need

Table 29: SUPPORT FOR COMPUTERS

Field of Technology	Nature of Support
semiconductors	IC development and manufacturing
magnetics	magnetic-storage development
low frequency (radio frequency)	component and circuit testing
microwave	high-speed IC development
electromagnetic compatibility	emissions and immunity testing
electronic data exchange	automating manufacturing

additional measurement support for complex digital-electronic products generally, and especially for computers. Currently, EEEL is conducting a measurement needs assessment to determine if there is a need for increased measurement support. As a part of this inquiry, EEEL is examining requirements for performance and reliability testing, including fault testing, at two levels: the component level, including both integrated components (very-large-scale integrated, or VLSI, circuits) and circuit assemblies; and the equipment level. EEEL hopes to complete this assessment in FY 1994. This assessment, and others that EEEL has conducted or is planning to conduct, are noted in Table 37 on page 48 in the section "Planning".

Video

Television, computers, and telecommunications are merging into advanced digital video systems that will provide new services for education, engineering, manufacturing, robotics, entertainment, medicine, defense, security, transportation, publishing, advertising, banking, and government. Video, audio, and text services will be fully integrated. These capabilities will augment the National Information Infrastructure.

However, progress in all the five technologies in Table 30 is required for the success of advanced video systems. EEEL provides support to industry for the three starred technologies through the work described in this section. Support for transmission is described in the sections "Microwaves" and "Optical-Fiber Communications" as part of the support for other communications services. Support for information storage is described in the section "Magnetics".

Table 30: VIDEO TECHNOLOGIES

* vision
* signal processing
transmission
information storage
* displays

Signal Processing

The hallmark of the new video systems is the simultaneous presentation of high-resolution images, full color depth, and smooth motion to take advantage of the remarkable capabilities of the human eye. Simultaneous presentation requires extraordinary information capacity that readily overloads transmission and storage systems. In response, industry and universities are developing compression techniques to minimize the amount of information required. The techniques exploit characteristics of both the image and the eye to present the minimum amount of information that the eye needs. Many competing compression techniques have been proposed in a flood of creative thinking that has produced remarkable compression levels. Unfortunately, industry lacks objective and accepted measurement methods for evaluating the resulting video quality against achieved compression ratios. This problem hampers both selection and further development of improved methods.

EEEL is responding by developing needed measurement methods. EEEL's strategy is to begin with application-specific measurement methods that are accessible at its present level of resources. As EEEL's resources increase, EEEL will expand its effort to encompass an array of methods with broader applicability. To support this work, EEEL has established a state-of-the-art video computer facility with the assistance of the Department of Defense. This facility is available to industry and enables testing video processing techniques through software emulation, without the need to build expensive prototype hardware. EEEL will contribute to the development of requirements for the National Information Infrastructure (NII), with a special focus on the requirements that advanced video systems must meet to interface with the NII.

Display

Full realization of the potential of advanced video systems will require major advances in flat-panel displays. Cathode-ray displays are too big, heavy, and expensive, particularly in large screen sizes. However, early flat-panel displays have been plagued with performance limitations and with manufacturing problems that have kept costs high. A major problem is the specification and objective assessment of display performance. Another problem is quality control during manufacturing.

EEEL is helping industry by developing measurement methods for display performance. As EEEL's resources increase, this work will be expanded to address an increasing spectrum of display characteristics, such as contrast ratio, sunlight readability, viewing angle, and object discrimination. The goal is to provide measurement methods appropriate for incorporation by industry in voluntary standards.

At the assumed level of resources, EEEL will not be able to provide measurement support for the manufacturing of displays. The measurement needs in this area are critically important to the industry. However, they are costly to address since they have all of the complexity of measurement support for integrated circuits with additional complications. Those complications include very large product sizes plus the mixing of technologies, such as semiconductors with liquid crystals, within individual displays. Further, the marketplace has not yet sorted out which technologies will dominate in displays, and thus the type of measurement support needed, which is highly sensitive to the materials technologies used, is not yet known. For these reasons, the question of committing to measurement support for the manufacturing of displays remains an open strategic issue of significance.

Vision

High-resolution vision technology is needed for most applications of advanced video systems including high-definition television and robotics (cameras) and document reading (scanners). For high-resolution camera performance, when viewing moving images in particular, no adequate methods currently exist for characterizing performance. As EEEL's resources increase during the planning period, EEEL will be able to undertake the development of the measurement methods for these cameras. Early work will focus on measures for camera noise and sensitivity.

Power

EEEL's work on measurement development in support of electrical equipment is driven by powerful forces. They derive principally from the need of the United States for increased electric power to support the continued expansion of the electrical services demanded by a population that is increasing in size and changing in geographical distribution. This need is heightened by the emergence of new products with high energy requirements, such as electric vehicles. To meet these demands, the United States has placed a high priority on achieving higher energy efficiency. It has also sought ways to increase the levels of power generated and transmitted by existing electric power systems. These efforts have lead to concerns about system reliability, power quality, and health effects. Each of these concerns is addressed below.

Energy Efficiency

The U.S. consumes $187 billion of electricity annually (1992). Because of the huge size of this number, even small changes in efficiency can have economic effects equivalent to the annual sales of entire industries. Energy losses occur in the generation, transfer, and use of electricity. Losses during transfer are believed to be in the range of 7 to 10 percent of the electric power generated. Internal losses in transformers are believed to account for about half of those losses. Transformers near generating stations increase voltage levels (and reduce current levels) prior to the transfer of electricity over long distances in order to reduce losses arising from the current levels. Transformers near end users reduce voltage levels (and increase current levels) to provide values suitable for applications. Losses during use occur in many types of applications. As noted above, motors consume about 60 percent of all delivered electricity; lighting, followed by heating, account for most of the remaining electricity generated (1985).[27] Small changes in the efficiency of power transformers and electric motors can have dramatic economic impact. These efficiencies, in turn, affect the price and thus the competitiveness of virtually every manufactured product.

The U.S. Government has recognized the significance of efficiency, especially in the face of the growing demand for electricity. In the Energy Policy Act of 1992, Congress directed the Executive Branch to develop requirements for the efficiencies of transformers and electric motors. EEEL is assisting, through the Department of Energy, by evaluating measurement methods for energy efficiency used by manufacturers of transformers and electric motors. EEEL will provide recommendations on the methods of choice. This process will help to standardize the methods in use and will support manufacturers in their efforts to develop, and demonstrate to users, improvements in efficiency. The improvements will be made through the use of new materials and new design strategies.

EEEL will also continue to develop improved measurement methods, supporting measurement reference standards, and calibrations services to support revenue metering in electric power systems. Through the requirements of state laws, the accuracy of all revenue meters manufactured in the United States (about 10 million per year) is made traceable to NIST.

Reliability

To increase the supply of electricity while still controlling capital costs, the suppliers are operating their generating equipment at, or even above, rated limits for extended periods of time. The suppliers are also increasingly interfacing with independent power producers who can augment the capacity of electric power systems. Finally, the suppliers are endeavoring to increase the amounts of power distributed through existing rights of way, in part because of the difficulty of establishing new rights of way for the delivery of electricity. These changes are increasing both the complexity of power systems and the stresses on their components, giving rise to increased concerns for reliability.

In an effort to preserve the reliability of power systems, the suppliers are moving steadily toward more sophisticated control and monitoring technology. Their aim is to gather more accurate information about energy production, transmission quality, and energy consumption in order to enable electric power systems to operate closer to their overall limits. EEEL will help by providing measurement support for key controlling devices, with a special focus on high-power switches including thyristors and insulated-gate bipolar transistors. EEEL will also develop measurement methods for characterizing key monitoring devices, in the form of new sensors that offer higher accuracy levels. With the increased resources that EEEL anticipates during the planning period, EEEL will extend this support to new optical-fiber sensors for voltage and current, as part of its broader effort on optical-fiber sensors. Such sensors are highly attractive for high-voltage and high-current environments since the non-conducting nature of the fibers makes them highly immune to interference. The optical-fiber sensors are also economically attractive.

A key threat to system reliability derives from the use of higher voltage and current levels to increase the amount of electric power that can be transmitted in a given right of way. The higher levels increase the electrical, thermal, and physical stresses on system materials, including electrically insulating materials (dielectric materials) in the form of gases, liquids, and solids. EEEL will help to resolve the associated problems through three principal contributions: fundamental research on the causes of electrical breakdown in insulating materials; development of improved methods for detecting and identifying partial discharge patterns that mark the onset of that breakdown; and development of improved methods for chemical analysis of the by-products of breakdown in insulation. These contributions will support: development of improved insulating materials; more effective use of existing materials; safe handling of insulating materials; development and manufacturing of power equipment; and field monitoring of insulation condition. A near-term goal is support for the development of *portable* chemical-analysis methods for on-site determination of insulation integrity. A long-term goal is support for *in service* computer-controlled monitoring of partial-discharge events and chemical by-products to provide real-time assessment of insulation integrity. This effort is an example of the pursuit of measurement immediacy for in-service systems. A special emphasis will be given to the gaseous insulating material, sulfur hexafluoride, which can support very high operating voltages in physically small equipment, but which has some toxic by-products of breakdown which raise safety concerns.

Power Quality

The quality of power delivered to customers is a factor of growing importance to both suppliers and customers. One cause for concern is the increasing application of solid-state power conditioning and control equipment to achieve more efficient variable-speed drives for motors and more efficient ballasts for fluorescent lights. This equipment provides significant savings in energy, but it can also introduce disturbances on power systems. These disturbances can take the form of voltage sags, surges, spikes, and harmonics. Such disturbances can affect sensitive electronic equipment, including the equipment used for power conditioning and control. EEEL is helping by developing measurement methods for detecting and diagnosing disturbances that degrade power quality. EEEL is also developing measurement methods for evaluating the effectiveness of mitigation techniques for protecting sensitive equipment from power disturbances.

Health Effects

There is increasing public interest in possible health effects from exposure to the electric and magnetic fields created by the transfer of electrical power, whether in overhead lines, in homes, or in the workplace. This interest has only been heightened by the need of the suppliers of electricity to use increased voltage or current levels, or both, to send more power down existing rights of way. Such increases require special design changes in the lines to prevent accompanying increases in electric and magnetic fields in the environment.

EEEL is responding by providing measurement capability needed to support a national research program on the health effects of the electric and magnetic fields. This program was established by the Energy Policy Act of 1992. It will require the accurate characterization of the electric and magnetic fields in the vicinity of power lines and electric appliances. EEEL will also provide continuing consultation on measurement issues arising in the bioeffects studies of the Department of Energy, the National Toxicology Program, and the Electric Power Research Institute.

Electric Vehicles

Electric vehicles represent one of the most important emerging demands for electricity. Led by California, the states with the greatest concerns for air quality have begun setting requirements for the introduction of electric vehicles. EEEL has responded by convening a workshop on electrical vehicles in collaboration with all major concerned departments of the Government. This workshop was attended by major manufacturers and researchers. At part of its contribution, EEEL will identify the measurement problems that must be resolved to enable the development and implementation of this new technology.

Electromagnetic Compatibility

The challenge of achieving electromagnetic compatibility has increased as the growth in the number of electronic and electrical systems has created more opportunities for mutual interference. The emergence of applications such as Personal Communications Services, wireless networks for computers, and communications and radar systems for intelligent highway and vehicle systems will only intensify the need to stay on top of the problems of mutual electromagnetic interference. At stake are the success of new products in the marketplace, the economic impact of the services that they will provide, and the safety of the public.

EEEL has been highly active in providing measurement methods to help the electronics and electrical-equipment industries cope with interference problems. However, EEEL is implementing some new strategic directions for its program and is weighing others that are the subject of considerable interest in industry, as described in the following sections.

Harmonization of Standards and Related Measurement Methods

At present, U.S. industry is coping with multiple standards for assuring tolerably low levels of electromagnetic emissions from its products. These standards are sourced in U.S. Government military requirements, U.S. Government non-military requirements (Federal Communications Commission, Federal Aviation Administration, and the Federal Drug Administration), industry voluntary standards, and emerging international standards. In many cases, these standards require very different types of measurement methods for use in proving compliance. Each of these methods may require an entirely different type of expensive test facility: anechoic (non-reflecting) chamber, screened room, open-air facility, or transmission-line apparatus. Industry wants fewer techniques that are more reliable. Industry also wants techniques that are more suitable for use on the factory floor, where electromagnetic compability problems can be discovered and corrected earlier. Current techniques require expensive and elaborate facilities. These techniques are often implemented only by testing laboratories where they are useful principally for evaluating products after manufacture -- a costly point at which to attempt corrections.

EEEL will help by providing measurement capability and technical assistance that will support standards-setting organizations in moving toward a smaller number of improved solutions, perhaps even to a single solution.

Immunity Measurements

To date, most standards relating to electromagnetic compatibility have stressed the control of unwanted *emissions* from products. New standards, and especially emerging international standards, increasingly stress control of the *immunity* of products to electromagnetic interference. Because U.S. Government standards do not address immunity, harmonization issues are particularly difficult for this area. Further, immunity testing is considerably more complicated than emissions testing. Emissions testing is largely external to a product and somewhat independent of the nature of the product. In contrast, immunity testing requires internal probing of a product to detect the penetration of electromagnetic energy, or the effects of that penetration, and is thus more product-specific. Further, immunity testing, as practiced to date, has often required rather expensive facilities capable of generating high-intensity interfering fields over wide frequency ranges. Thus, the discovery of new methods that are affordable is again a major need. In response, EEEL will focus a major part of its efforts on providing measurement capability supportive of immunity testing and will seek to discover methods that address these several concerns.

International Standards Participation

In a recent industry survey of measurement-related issues in electromagnetic compatibility, EEEL found strong industry interest in having NIST assume a leadership role in international standards bodies addressing electromagnetic compatibility.[28] EEEL's response to this request will have to be considered in the context of NIST's broader inquiry into the appropriate role for the U.S. Government in international standards, as discussed on page 22.

Electronic Data Exchange

To implement new management strategies for improved competitiveness, such as those outlined in Table 17 on page 17, manufacturers must meet a number of needs. The need for improved measurement capability has already been discussed. In addition, manufacturers need several types of data in computer-accessible digital formats that can be shared among manufacturers and between manufacturers and suppliers. In response to this common need, a number of collaborative efforts have emerged to promote the development of standards for data structures suitable for electronic data exchange over information networks. Such data exchange serves virtually all goals in Table 17; that is, it promotes total-quality management, flexible manufacturing, and collaborative efforts within and among companies, including so-called virtual corporations. Such data exchange benefits from broadly accessible networks, such as those proposed for the National Information Infrastructure.

International Participants

Table 31: PARTICIPANTS' FUNCTIONS
concept development
concept standardization
program coordination
program funding

The participants in these collaborative efforts include individual companies, industry organizations, national and international standards bodies, and government agencies. They serve a variety of functions, as indicated in Table 31, in different efforts that have varying degrees of interaction with each other. Among the participating organizations are the International

Standards Organization, the International Electrotechnical Commission, the Advanced Research Projects Agency of the Department of Defense, the National Initiative for Product Data Exchange (a coordinating body with headquarters at NIST), and several NIST Laboratories, including EEEL.

Major Goals

Table 32: MAJOR GOALS
design-description universality
electronic marketplace
manufacturing-process automation

The goals of this international effort are ambitious. However, the potential impact is so high that it has stimulated remarkable levels of interest and support. Three of these goals are especially relevant to the industries that EEEL serves. They are shown in Table 32. The first goal is to develop standardized data structures for describing product designs in a universal manner, so that they can be shared by users with different automated design tools (such as computer-aided design systems) operating over computer networks. Such universality will promote collaborative design efforts. The second goal is to create an electronic marketplace that fosters collaborative efforts. A major step in this direction is to create standardized data structures for component descriptions that would be made available through computer networks. Initially, these descriptions would contain specifications only; but later they might contain information for simulating component performance in circuits. This electronic marketplace would aid manufacturers and suppliers in locating each other, working together, and making sales. The third goal focuses on the development of factory-automation software that is modularized in a standard manner. The standard modules would enable compatible substitution of software modules from different vendors to implement process improvements or process alterations for making different products. This work supports both quality control and flexible manufacturing.

There are several broad observations about these early efforts that are worth making. They center on computer software, computer data, and related standards for compatibility in networked environments. They focus on describing and making components and subassemblies of components, as opposed to making materials, equipment, or systems. They support principally manufacturers and their suppliers. They help manufacturers complete all four of the basic steps required to realize competitive products in the marketplace. These steps were outlined in Table 15 on page 16. Specifically, for development, these efforts aid product design; for manufacturing, they aid process control; for marketplace exchange, they aid product specification; and for after-sales support, they aid maintenance (parts replacement).

EEEL's Role

EEEL will contribute to reaching all three goals in Table 32. For them all, EEEL will support harmonization of standards by developing methods for testing for compatibility among the different potential standards developed through the various standardization efforts. EEEL will provide an impartial forum for resolving conflicts among these efforts. EEEL will also provide technical support for the development of the standards. EEEL is initially emphasizing pursuit of the first goal in Table 32: design-description universality. But, as resources increase during the planning period, EEEL will increase its efforts toward the two other goals, as well. For the electronic marketplace, EEEL is already demonstrating existing technology for data exchange of general product information over a national network. This effort will soon be extended to data on component specifications. For manufacturing-process automation, EEEL will assist SEMATECH -- the semiconductor manufacturing technology consortium -- as it makes the first attempt to implement this approach to manufacturing. EEEL's work with SEMATECH will require successful development of the factory models for semiconductor manufacturing, described on page 24, with their many dependencies on excellence in measurements. Later, EEEL will extend a similar type of support to the manufacturing of other electronic products.

National Electrical Standards

At noted above, high accuracy in measurements is very important to research and development, manufacturing quality control, and marketplace exchange. Measurements of electrical quantities are particularly important. In fact, electrical quantities are the common currency of measurements; that is, many non-electrical quantities are converted into electrical quantities to facilitate measurement by electronic instrumentation.

The Central Role of Electrical Standards

Measurements of electrical quantities, and thus of many other quantities, rest upon accurate measurement of four fundamental electrical quantities: dc voltage, dc current, and dc resistance, and capacitance. Measurements of ac electrical quantities, while more complex, are verified by comparison with measurements of these quantities. Thus, the accuracy obtained in these fundamental quantities is both the basis for, and the limitation upon, the accuracy obtained in measuring many other electrical quantities. For this reason, the accuracy of the national electrical standards, developed by EEEL, underpins the measurement capability provided in support of virtually all fields of technology described in this plan. Each standard provides highly accurate levels of an electrical quantity and thus enables the calibration of instrumentation used for measurement.

EEEL is constantly striving to improve the accuracy of these standards in response to the needs of industry for ever higher levels of performance. Keeping ahead of these needs has become increasingly difficult. The gap in time between the achievement of fundamental advances in levels of accuracy and the application of those levels in industry has been narrowing. In pursuit of the needed advances, EEEL is engaged in the process of periodically developing new standards for the fundamental electrical quantities. EEEL is focusing on two principal goals for new standards: higher levels of accuracy; and easier replication for direct use by other organizations. Direct use increases delivered accuracy by reducing the number of intermediate steps in the transfer of accuracy; each step unavoidably degrades delivered accuracy. Direct use also reduces the labor required to transfer accuracy from NIST to other organizations.

Exploiting Quantum Phenomena

To achieve these goals for new national standards, EEEL has turned to quantum phenomena. They enable relating electrical quantities to unvarying fundamental atomic constants, such as the charge on an electron, and to selected quantities that can be measured very accurately, such as frequency. Frequency (or equivalently, time) is the quantity in nature that NIST can measure with most accuracy (about 1 part in 10^{14}). Successful pursuit of quantum standards requires detailed fundamental research to understand thoroughly the underlying physics.

EEEL has successfully developed a quantum standard for dc voltage in the form of a superconductor integrated circuit that employs the ac Josephson effect. This standard was introduced on page 28 in the section "Superconductors". A commercial version is now available. The most advanced version of the voltage standard is used by industry to support calibration of the most accurate voltmeters during their manufacture. EEEL is now attempting to adapt the technology in this standard to provide an ac voltage standard. EEEL has also developed a quantum standard for dc resistance in the form of a semiconductor integrated circuit that employs the quantum Hall effect. EEEL is working toward the commercialization of this technology in the next few years. EEEL's newest direction, which has a longer time horizon, is the pursuit of a quantum standard for electric current, based on counting individual electrons. This technology may also provide an alternative approach to a capacitance standard and may thus facilitate comparison with the present approach based on dimensional measurements. This comparison enables a more direct all-electronic route to determination of a critically important atomic constant, the fine-structure constant. EEEL is also exploring an electronic method for monitoring mass, based on the quantum standards for dc voltage and dc resistance. The present international standard for mass is a platinum-iridium kilogram mass, which has at least two important limitations: it changes over time in ways that are not fully understood, and it does not provide a readily accessible reference for international use. Mass is the only unit in the International System of Units (the SI Units) that is still represented by a physical object.

Continued success in the implementation of electrical standards based on quantum phenomena could motivate a future redefinition of the International System of Units to provide definitions more readily implemented by a broad range of users. The present definitions are not readily implemented in experiments.

International Representation

EEEL's work on the national electrical standards contributes to the efforts of the International Committee on Weights and Measures to advance the quality of measurements. NIST is the official representative of the United States to this treaty organization and has established a leadership position for this country in electrical standards.

CUSTOMER SURVEY

While EEEL's primary customers are the electronics and electrical-equipment industries, EEEL also supports other government agencies (Federal, state, and local), educational institutions, and the general public. EEEL serves the research community wherever it is located -- in industry, government agencies, or educational institutions. EEEL thinks of its customers as falling into two broad groups: direct customers and indirect customers.

Direct Customers

EEEL defines its direct customers as *organizations that are direct beneficiaries* of EEEL's products, services, or significant information. They include all organizations participating in collaborative research with EEEL and all other-agency and industrial organizations who fund EEEL's work. The customers also include the committees on which EEEL staff serve and the organizations whose members take courses taught by EEEL. They do *not* reflect casual contacts, in the form of lab tours or telephone calls, or requests for publications; these interactions number in the several thousand per year. Given this definition, EEEL served about 2150 different customer

Table 33: CUSTOMER ORGANIZATIONS BY TYPE

industry	72%
government agencies	
civilian	3%
military	5%
national laboratories	1%
educational institutions	6%
foreign countries	13%
other NIST Laboratories	1%
(effects of rounding)	101%

organizations during the five-year period ending in 1991, the year of the most recent analysis of the full customer base.

Table 33 shows how those customer organizations break down by type of organization. The category "industry" includes individual companies and industry groups of various kinds, such as trade associations and consortia. The high presence of industry and government agencies is consistent with EEEL's definition of its mission. The category "foreign" includes foreign government agencies, including scientific and metrology laboratories, plus foreign subsidiaries of U.S. owned companies, and foreign companies from which NIST feels the United States can gain through collaboration.

EEEL's customers include 102 of the Fortune 500 companies and 44 of the top 100. Table 34 shows the percentages of companies, from each of several key categories of Fortune 500 companies, that are EEEL's customers. Not shown in the table, EEEL serves all three major automobile manufacturers and a very large number of companies (42) in the pharmaceutical, medical, and health areas, among many others.

Table 34: COVERAGE OF FORTUNE 500 BY CATEGORY

aerospace	82%
electronics	64%
scientific/photographic	63%
computer/office equipment	50%
chemical	24%

EEEL's customers span a broad spectrum of sizes. EEEL serves the biggest companies in the United States and interacts extensively with the smaller ones. The bigger companies have worldwide clientele and are major economic forces; many have the U.S. Government as a major customer. EEEL may serve a dozen or more locations for the largest corporations. The smaller companies serve many specialized needs. Some of the smaller companies are the most sophisticated in the world in their specialties. Frequently, the smaller companies are instrument manufacturers or consulting firms.

Table 35 shows the approximate distribution of EEEL's industrial customer organizations by size, specified in terms of number of employees. An accurate distribution is difficult to determine since size data are not readily available for about half of EEEL's rather large number of industrial customers (more than 1500). However, from available information EEEL estimates that about half of its U.S. industrial customers meet the usual definition of a small company (fewer than 500 employees). About 10 to 15 percent of the small companies served have fewer than 20 employees, thus the nominal 12 percent shown in the table.

Table 35: INDUSTRIAL CUSTOMER ORGANIZATIONS BY SIZE

large (above 500 employees)	50%
small (20 to 500 employees)	38%
very small (below 20 employees)	12%
	100%

Indirect Customers

EEEL defines its indirect customers as the *customers of EEEL's direct customers*. Because of society's broad dependence on electronic products and electricity, EEEL's indirect customers span virtually the entire scope of the electronics industry, most other industries, and the general population. For example, virtually all watthour meters used for revenue metering in the U.S. are calibrated against reference standards that are themselves calibrated by NIST for its direct customers -- the manufacturers of the watthour meters. Similarly, EEEL provides measurement support to other Government agencies, such as the Department of Defense and the Department of Energy, whose services, in turn, benefit the entire nation.

PLANNING

Approach to Planning

EEEL's approach to strategic planning is best described as *industry oriented*. That is, at the most general level, EEEL's approach is to determine what is most needed by the industries that EEEL supports to make them competitive, and then to determine which of those needs NIST can and should address within its broad charter. This industry-oriented approach to planning is demanding because it requires broad knowledge of the industries served. However, it is very effective in meeting the broad goals pursued here: economic growth and improved competitiveness. To pursue these goals, the contributions of maximum leverage must be identified, no matter where they occur in the several steps that manufacturers must complete to realize competitive products in the marketplace (Table 15 on page 16), and no matter what scientific or engineering disciplines are required to address them, and no matter which organizational units within NIST are needed to respond. This is EEEL's approach. It will benefit from NIST's current effort to provide an improved framework for collaborative projects among major organizational units.

This industry-oriented approach is very different from an approach based on *organizational units* or on *traditional scientific or engineering disciplines* alone. In such approaches, managers examine the skills of a given organizational unit, or the capabilities of a given discipline, and ask what problems can be solved by this unit or with these capabilities. While these are very important considerations for planning, they do not as readily lead to identifying the projects of maximum leverage for achieving broad goals like economic growth and competitiveness.

Because EEEL strives for an industry-oriented approach, EEEL describes its strategic plans in a format that is sensible to the supported industries. EEEL does not feel that a description by organizational unit is as effective, since the aim is to focus outward on the customer, rather than inward. Therefore, EEEL's organizational structure is not referenced in this plan. EEEL draws on the capabilities of any part of its organizational structure, as needed, to respond to any of its strategic directions. EEEL wishes to continue to draw on the capabilities of NIST's other major organizational units as needed. EEEL continues to offer its own capabilities to these other units in response to important strategic directions that they have identified.

The relationship of EEEL's organizational structure to the fields of technology that provide the structure for this strategic plan is described in EEEL's *1994 Program Plan.*[29]

Planning Documents

EEEL reflects its plans and accomplishments in five types of published documents, as shown in Table 36. Also shown are typical publication frequencies and time horizons. Most of these documents have been referenced above. Each document is described briefly below:

> The measurement needs assessments provide EEEL's analyses of the measurement problems for which the electronics and electrical-equipment industries most need NIST's assistance. These assessments are prepared in consultation with U.S. industry and other NIST Laboratories. The assessments are published on an irregular schedule, either individually or in groups as they are completed. EEEL has published groups of measurement needs assessments in three of the last five years. The most recent assessments are contained in *Measurements for*

Competitiveness in Electronics. For two fields in the table -- optical signal processing and optical computing -- no measurement needs assessments are yet planned because these fields are still in early stages of development.

The strategic plan -- this document -- describes the overall directions of EEEL's programs in response to industry's needs.

Table 36: PUBLISHED PLANNING DOCUMENTS

Document	Frequency of Publication (years)	Time Horizon (years)
needs assessments	irregular	10
strategic plan	2	5
program plan	1	5
accomplishments	1	1 backward
impact studies	irregular	10 backward

The program plan describes the implementation of the strategic directions in the strategic plan through specific programmatic activities, with a special emphasis on plans for the current year and on selected plans for four additional years into the future.

The report on accomplishments describes the technical accomplishments of EEEL's program for the most recently completed year. This report was published for the first time at the end of 1993.

The impact studies measure the impact of EEEL's work. They are published on an irregular schedule, as they are completed. They are described in the section "Measuring Progress and Impact" on page 49.

In addition to these published documents, EEEL employs a list of criteria for selecting new work. The purpose of the list is to assure that the most important factors have been considered.

Table 37 provides more information about the two types of documents that are irregularly published: the measurement needs assessments and the impact studies. In addition, the table shows two key activities that support the measurement needs assessments: surveys of industry's measurement needs conducted by EEEL to support the assessments, and reviews of the assessments by industry. The table includes both documents completed in FY 1990-1993 and documents planned for FY 1994-1995. The key at the bottom of the table indicates the type of documents referenced in the

Table 37: MEASUREMENT NEEDS AND IMPACT DOCUMENTS

Fields	'90	'91	'92	'93	'94	'95
semiconductors	a	r,a	i	a,s	a,s	a
magnetics	a	.	r	a	.	.
superconductors	a	.	.	a,i	.	.
low frequency	.	.	.	.	.	a
microwaves	a,r	.	.	a	.	.
lightwaves						
lasers	a	r	.	a,r	.	.
optical-fiber communications	a		i	a,r	.	.
optical-fiber sensors	a	.	.	a,r	.	.
optical information storage	.	.	.	.	.	a
optical signal processing	.	.	.	.	.	.
optical computing	.	.	.	.	.	.
computers	.	.	.	.	a	.
video	a	.	.	r,a	.	.
power	.	.	.	.	i	a
Cross-Cutting Fields						
electromagnetic compatibility	a	r,i	.	r,a	.	.
electronic data exchange	.	.	.	.	.	a
national electrical standards	.	.	.	.	.	a

a = assessment of industry's measurement needs
r = review of needs assessment by industry
s = survey of industry's measurement needs
i = impact study

table. A full list of all of the documents referenced in Table 37 is contained in an endnote.[30]

The reviews referenced in the table may be conducted before or after the publication of the measurement needs assessment for a given technical field. If conducted afterward, the reviews contribute to the next publication of the assessment for the technical field.

The surveys referenced in the table are developed using written questionnaires, telephone calls, or visits to make contact with industrial technical and managerial personnel.

The impact studies referenced in the table are sponsored by EEEL or the NIST Program Office and are conducted with the assistance of economists and industry experts to determine how completed work has affected industry.

EEEL employs other mechanisms, as well, to gather information important for planning. These other mechanisms may or may not result in formal documents. Among them are individual contacts with industry representatives by all staff members, round-robin measurement intercomparisons, and workshops. For example, EEEL, in cooperation with other NIST Laboratories and Government agencies, held a workshop in October, 1993 to determine the requirements, technical barriers, and innovations associated with emerging components for electric and hybrid-electric vehicles. This workshop is providing the basis for subsequent efforts to identify associated critical measurement needs. Further, EEEL, in cooperation with the Advanced Research Projects Agency, is planning a major workshop on the measurement needs of the semiconductor industry for January-February, 1995. It will have broad representation from the industry.[31]

MEASURING PROGRESS AND IMPACT

EEEL uses a variety of means to measure the progress of its program toward its technical objectives, and to measure the economic impact of the program, the ultimate measure.

Measuring Technical Progress

EEEL reports on technical progress in the five documents shown in Table 38. The most comprehensive is the program plan, introduced above as one of EEEL's published planning documents. The program plan contains detailed milestones for the current year and additional milestones for four years forward. These milestones number in the hundreds. The program plan also reports on accomplishments (completed milestones) for the past year. Key accomplishments are summarized annually in a form suitable for non-technical audiences in a published report. This report has just been issued for the first time. EEEL's Divisions also develop internal quarterly management reports and internal monthly technical highlights, both of which report on technical progress. Finally, EEEL publishes a technical progress bulletin as needed (typically about four times a year). The bulletin provides abstracts of all new technical papers written by the EEEL staff since the last publication.

Table 38: MEASURING TECHNICAL PROGRESS

Document	Frequency
program plan	yearly
accomplishments	yearly
management reports	quarterly
technical highlights	monthly
technical progress bulletin	as needed

Measuring Economic Impact

EEEL sees its impact daily in convincing forms: high activity associated with delivery of its findings, as summarized in Table 3 on page 6; speed of industrial adoption of findings; clamor for more assistance; reports of impact from industry; and continued funding from other agencies.

Table 39: IMPACT STUDY TRAITS
Formality
anecdotal
analytical
Scope
single project
entire program
Chronology
retrospective
prospective

EEEL documents this impact in a variety of studies that have the characteristics outlined in Table 39. The information developed may be anecdotal or analytical in nature. The studies may address individual projects or entire program areas. The studies may be prospective or retrospective in nature.

The analytical studies are the most difficult and expensive to conduct because measurement technology is *implicit* in nearly *every aspect* of industry's performance; thus both identifying and isolating all of the effects are difficult. Of course, this implicit, or infrastructure, character of measurement technology is the also the reason for its high impact.

The *analytical* studies provide "benefit:cost" ratios, social rates of return,[32] or other indicators of economic impact. However, EEEL, in its most recent studies, is seeking expression of economic impact in terms of social rates of return to facilitate comparison with broader literature on the impact of innovation.

In the discussion below, the overall conclusions that can be drawn from the most recent impact studies are cited. Then, findings from four recent analytical impact studies are summarized. All of these impact studies are referenced in Table 37 on page 48. Three of these studies are both retrospective and prospective in nature. The fourth study is retrospective in nature. Additional studies will be forthcoming.

These impact studies are a part of a continuing series of analytical studies that EEEL has conducted over a period extending back more than ten years. Several of the earlier studies were described in EEEL's *1991 Strategic Plan*. They addressed principally the semiconductor program and the optical-fiber communications program.

The studies reported in this 1994 plan are those completed since the publication of the 1991 plan. There is one partial exception: the study on optical-fiber communications. This study was reported in the 1991 plan and was expanded following the publication of that plan. The findings of the expanded study are reported here.

Overall Conclusions

EEEL's most recent analytical impact studies found social rates of return above 100 percent, as shown in Table 40. These values are lower limits since the studies could not capture all of the benefits. Even so, they are higher than the median for selected industrial innovations studied by Edwin Mansfield (18 innovations with median of 56 percent) and J.G. Tewksbury (20 innovations with median of 99 percent) in two important studies.[33] The EEEL values also fall within or above the range cited by Dr. Allan Bromley, recently the President's Science Adviser, as applicable to all basic and applied research and development: 20 to 200 percent.[34]

Table 40: MEASURING ECONOMIC IMPACT

Year of Study	Field of Technology	Social Rate of Return (percent)
1992	Semiconductors: Electromigration	117
1992	Lightwaves: Optical-Fiber Communications	423
1991	Electromagnetic Compatibility	266
for comparison		
1977	Mansfield (18 innovations)	56
1980	Tewksbury (20 innovations)	99

Semiconductors: Electromigration

The U.S. semiconductor industry was surveyed to determine the impact of measurement methods developed by EEEL for characterizing electromigration in the very thin metallic interconnections within semiconductor integrated circuits (1992).[35] The migration of conducting material is driven by the impact of the tremendous current densities flowing in these interconnections. These densities approach a million amperes per square centimeter, a thousand times greater than the current densities in household wiring. The study found that the manufacturers of semiconductors attributed $27 million of benefits over the period 1981 to 2001 to the availability and use of the NIST research in this area. The benefits were derived from reduced marketplace transactions costs and reduced overall manufacturing costs. Also found was increased efficiency in research and development on metallization. EEEL's investment was $1.7 million from 1981 to 1991. The data indicated a social rate of return of 117 percent. Additional benefits were known to have occurred but were not quantifiable. They include benefits to academic researchers and to manufacturers of testing systems, who indicated that they would not exist without the NIST contribution.

Lightwaves: Optical-Fiber Communications

The U.S. optical-fiber industry was surveyed to determine the economic impact of 22 voluntary industry standards for determining the critical properties of optical fibers (1992).[36] EEEL provided the measurement basis for these standards. The result was $65 million in cost savings over the period 1981 to 1995. The cost savings were principally in the form of reduced marketplace transactions costs between producers and users of optical fibers, but "an important indirect effect was a much faster rate of growth for the optical fiber market and hence for the U.S. optical fiber industry." One manufacturer participating in the study attributed a *factor* of 25 increase in sales to the EEEL-supported standards. In comparison, the total costs incurred by EEEL to realize these benefits were about $3 million over the period 1981 to 1989. The data indicated a social rate of return of 423 percent. Additional benefits were obtained but were not readily quantifiable.

Electromagnetic Compatibility

U.S. industry was surveyed to determine the impact of NIST measurement methods on manufacturers' efforts to control unwanted electromagnetic emissions from their equipment and to protect their equipment from electromagnetic interference.[37] He found $269 million in benefits to industry over the period 1980 to 1996, attributable to EEEL's work. The benefits were in the form of reduced marketplace transactions costs and reduced costs both in developing test facilities and in conducting tests for electromagnetic compatibility. EEEL incurred costs of $12 million over the period 1980 to 1991 to provide the benefits. The data indicated a social rate of return of 266 percent. Benefits to the automotive industry alone reached $17 million per year in 1991. There were other benefits that could not be captured.

Superconductors

The U.S. superconductor industry was surveyed to determine the economic impact of EEEL's program in support of three key areas: low-temperature-superconductor wire and magnets, low-temperature-superconductor electronics, and high-temperature-superconductor materials and electronics. This study is interim in nature since the industry is still in its infancy. The largest market segment is for superconductor magnets, dominated by magnets for magnetic resonance imaging, with much smaller markets for other applications such as superconductor measurement instrumentation. The most recent estimate for the world market for superconductor products is $172 million in 1988.[38]

For all of studied areas combined, the survey response was excellent, with 33 of 40 companies responding. However, the amount of economic data reported by industry was very limited and not sufficient to support a calculation of the social rate of return. Even so, the qualitative responses were very informative. For example 79 percent of the responding companies indicated that they had benefited from contacts with NIST personnel. Also, 76 percent indicated or implied that they had a better understanding of their existing or anticipated company products or processes as a result of the NIST program. Smaller but still significant percentages of the respondents, from 39 percent down to 12 percent, indicated benefits in several other forms: improved ability to meet customer specifications; new research-and-development directions; improved ability to secure contracts or grants; improved marketing or contract performance through improved ability to meet requirements for traceability or measurement assurance; and anticipation of development of new products as a result of the NIST interaction.[39]

ENDNOTES

1. All shipments figures were compared in current dollars. They are also estimates since no firm shipment data for 1992 were available at the time of publication of the referenced documents. Employment figures are industry data. Industry data reflect all products and services sold by establishments in the named industry, whether or not the products are classified in that industry. Product data reflect all products classified in the named industry and sold by all industries. There is some overlap in the products of these industries compared. Some electronic products are included in the automotive and aerospace industries. This overlap arises because there is no set of codes in the Standard Industrial Classification (SIC) System, on which all of the figures in the table are based, that is devoted exclusively to the electronics industry. The data for the largest five manufacturing industries came from the following sources: (a) Electronics Industry: *1993 Electronic Market Data Book*, Electronic Industries Association, pp. 2, 5 (1993). (b) Chemical Industry: *1993 U.S. Industrial Outlook*, International Trade Administration, U.S. Department of Commerce, p. 11-1 (January 1993). (c) Automotive Industry: The figures shown include both the motor-vehicle and supporting parts industries. *1993 U.S. Industrial Outlook*, pp. 35-1 and 35-18. (d) Petroleum Refining Industry: The employment figure is from 1990, the year of most recent data, and is used as an estimator for 1992. *1993 U.S. Industrial Outlook*, p. 4-1. (e) Aerospace Industry: *1993 U.S. Industrial Outlook*, p. 20-1.

2. The definition used for the electrical-equipment industry was developed at NIST, but was influenced by the products of interest to the members of the National Electrical Manufacturers Association. The definition excludes products which employ electrical components for practical applications. For example, excluded are household appliances, transportation equipment, and manufacturing equipment. Most of these excluded products are as much the products of other industries. Further, the excluded products are difficult to bound because electricity is used so widely. Also, excluded from the definition are electronic products. For the most part, they are the products that apply electricity in electrical form rather than as motion, light, heat, or electrolytic action.

3. Preliminary figures for 1992 from the Edison Electric Institute, Washington, DC (November 1993).

4. *1993 Electronic Market Data Book*, Electronic Industries Association, p. 5 (1993).

5. *Measurements for Competitiveness in Electronics*, First Edition, Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, NIST Report No. NISTIR 4583 (April 1993).

6. *Electronics and Electrical Engineering Laboratory: 1994 Program Plan*, Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, NIST Report No. NISTIR 5337 (December 1993).

7. President Bill Clinton, "A Vision of Change for America", February 17, 1993. The specific page numbers for the goals listed in Table 1 are these: (a) p. 33; (b) p. 37; (c) p. 38; (d) p. 38; (e) p. 38; (f) p. 41; (g) p. 42; (h) p. 42; (i) p. 45; and (j) p. 45.

8. The Technology Reinvestment Program will fund new work in FY 1994 as well. Its future thereafter will apparently be determined on a year-by-year basis.

9. Some definitions of fundamental research exclude from consideration any research undertaken with a view to achieving practical benefits from its successful completion. That is, they add the notion of lack of specific purpose, or for the purpose of advancing knowledge only, to the definition, even if the nature of the work is unaffected by this addition.

10. EEEL in previous strategic plans has reported also the number of industrial research associates working in EEEL. However, the cooperative research and development agreements that NIST has developed with industry have made this category irrelevant. The agreements define a general relationship that enables researchers from participating companies to work at NIST for varying lengths of time without additional special agreements for each researcher. Unrelated to these agreements, guest scientists come to NIST from U.S. universities and foreign countries.

11. All shipments figures in the table are *product data* in current dollars. They are also estimates since no firm shipment data for 1992 were available at the time of publication of the referenced documents. Employment figures are industry data. Industry data reflect all products and services sold by establishments in the named industry, whether or not the products are classified in that industry. Product data reflect all products classified in the named industry and sold by all industries. There is some overlap in the products listed in the table. Some electronic products are included in the automotive and aerospace industries. This overlap arises because there is no set of codes in the Standard Industrial Classification (SIC) System, on which all of the figures in the table are based, that is devoted exclusively to the electronics industry. The superscripts in the table refer to the notes that follow: (a) *1993 Electronic Market Data Book*, Electronic Industries Association, pp. 2, 5 (1993). (b) *1993 U.S. Industrial Outlook*, International Trade Administration, U.S. Department of Commerce, p. 11-1 (January 1993). (c) The figures shown include both the motor-vehicle and supporting parts industries. *1993 U.S. Industrial Outlook*, pp. 35-1 and 35-18. (d) The employment figure is from 1990, the year of most recent data, and is used as an estimator for 1992. *1993 U.S. Industrial Outlook*, p. 4-1. (e) *1993 U.S. Industrial Outlook*, p. 20-1.

12. Bureau of Economic Analysis, Survey of Current Business and Office of Management and Budget as of March 9, 1993 as published in *Science & Engineering Indicators -- 1993*, National Science Board, National Science Foundation (1993).

13. The definition used for the electronics industry is that of the Electronic Industries Association. All data in the table come from the *1991 Electronic Market Data Book*, Electronic Industries Association (1991) from the pages shown. These data in turn are based almost exclusively on data collected by the Bureau of the Census of the U.S. Department of Commerce. The superscripts in the table refer to the notes that follow: (a) p. 68; (b), p. 68, however, the breakdown shown was estimated by NIST directly from data in "Semiconductors, Printed Circuit Boards, and Other Electronic Components, *Current Industrial Reports*, No. MA36Q(89)-1, Bureau of the Census, U.S. Department of Commerce, p. 1 (September 1991); (c) p. 36; (d) p. 38; (e) p. 36; (f) p. 36; (g) p. 37; (h) p. 48; (i) p. 52; (j) p. 48; (k) p. 51; (l) based on revised data computed with EIA assistance from the *Current Industrial Reports*, of the Bureau of the Census, U.S. Department of Commerce, including "Radio and Television Receivers, Phonographs, and Related Equipment", No. MA36M(89)-1, pp. 1-3 (October 1991), "Computers and Office and Accounting Machines", No. MA35R(89)-1, p. 4 (October 1991), and "Communication Equipment, and Other Electronic Systems and Equipment", No. MA36Q(89)-1, p. 1 (September 1991); (m) pp. 99-101.

14. The definition used for the electrical-equipment industry was developed at NIST, but was influenced by the products of interest to the members of the National Electrical Manufacturers Association. The definition excludes products which employ electrical components for practical applications. For example, excluded are household appliances, transportation equipment, and manufacturing equipment. Most of these excluded products are as much the products of other industries. Further, the excluded products are difficult to bound because electricity is used so widely. Also, excluded from the definition are electronic products. For the most part, they are the products that apply electricity in electrical form rather than as motion, light, heat, or electrolytic action.

15. The references used for determining U.S. shipments were all developed by the Bureau of the Census, U.S. Department of Commerce and include the *Current Industrial Reports*, the *1987 Census of Manufactures*, and the *1987 Annual Survey of Manufactures*. Data on shipments for 1990 were not available for all products; in such cases, the two years of most recent data (selected from 1990, 1989, 1988, 1987, and 1982 in different

cases) were used in a straight-line projection to obtain an estimate of the 1990 level. The data are collected in the categories of the Standard Industrial Classification (SIC) System. Because only part of the products in some of the SIC categories are applicable to the electrical-equipment industry, and because the fraction applicable is not known with precision, estimates had to be made to develop a total figure for the industry. This has led to higher levels of uncertainty in some product categories than in others. For example, the actual value associated with *electrical insulation*, in particular, may vary considerably from that reported here.

16. Preliminary figures for 1992 from the Edison Electric Institute, Washington, DC (November 1993).

17. *Electric Motors and Drives: Markets, Trends and Opportunities: Phase 1 - Motors*, Resource Dynamics Corporation (prepared for the Electric Power Research Institute), p. 4 (January 1991).

18. For example, at the end of FY 1990, when a count was last made, EEEL had 51 collaborative efforts in place as follows: Manufacturing Engineering Laboratory (7), Chemical Science and Technology Laboratory (12), Physics Laboratory (6), Materials Science and Engineering Laboratory (13), Building and Fire Research Laboratory (3), Computer Systems Laboratory (2), and Computing and Applied Mathematics Laboratory (8). Some of these collaborative efforts involved the transfer of funds.

19. A detailed discussion of these relationships is provided in Chapter 1 of *Measurements for Competitiveness in Electronics*, First Edition (April 1993).

20. *Semiconductor Technology: Workshop Conclusions*, Semiconductor Industry Association, p. 6, (1993). This document is referred to informally, but widely, within the semiconductor industry as the "semiconductor roadmap".

21. *Market Opportunities in Optoelectronics: Technology Roadmap Program*, Optoelectronics Industry Development Association, pp. 23-60 (June 1993). Also addressed are industrial-equipment, aerospace, computer, automotive, and consumer markets for optoelectronic products.

22. *Semiconductor Technology: Workshop Conclusions*, Semiconductor Industry Association, p. 6, (1993). This document is referred to informally, but widely, within the semiconductor industry as the "semiconductor roadmap".

23. One particle per 10 cubic feet of air.

24. From World Business Publications, as published in *Superconductor Week* (February 27, 1989).

25. Stephen G. Anderson, "Review and Forecast of Laser Markets: 1994", *Laser Focus World*, pp. 62-76 (January 1994).

26. *Market Opportunities in Optoelectronics: Technology Roadmap Program*, Optoelectronics Industry Development Association, pp. 23-60 (June 1993). Also addressed are industrial-equipment, aerospace, computer, automotive, and consumer markets for optoelectronic products.

27. *Electric Motors and Drives: Markets, Trends and Opportunities: Phase 1 - Motors*, Resource Dynamics Corporation (prepared for the Electric Power Research Institute), p. 4 (January 1991).

28. Ramon C. Baird, "Summary Report on Measurement Related Issues, Problems, and Requirements Associated with Electromagnetic Compatibility: Results of a Limited Survey", p. 34 (September 30, 1993).

29. *Electronics and Electrical Engineering Laboratory: 1994 Program Plan*, Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, p. 11 (December 1993).

30. All documents noted in Table 37 are shown below. They cover the period 1990 to 1995.

Semiconductors

1990	a	Chapter 2, "Semiconductors", *Emerging Technologies in Electronics*, Second Edition, Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, Report No. NISTIR 90-4260 (February 1990).
1991	r	Industry review of draft: Robert I. Scace, *Metrology for the Semiconductor Industry*, Report No. NISTIR 4653 (September 1991).
1991	a	*Metrology for the Semiconductor Industry*
1992	i	Albert N. Link, *Economic Impact on the U.S. Semiconductor Industry of NIST Research in Electromigration* (January 1992).
1993	a	Chapter 4, "Semiconductors", *Measurements for Competitiveness in Electronics*, First Edition, Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, NISTIR 4583 (April 1993).
1993	s	"$Hg_{1-x}CD_xTe$ Characterization Measurements: Current Practice and Future Needs", *Semiconductor Science and Technology*, Vol. 8, pp. 753-776 (1993).
1994	a	Compound semiconductor measurement needs assessment, to be completed in 1994.
1994	s	Optical characterization methods for materials, processing, and manufacturing in the semiconductor industry, to be completed in 1994.
1995	a	Measurement needs assessment for semiconductors broadly, to be completed in 1995.

Magnetics

1990	a	Chapter 4, "Magnetics", *Emerging Technologies in Electronics*, Second Edition.
1992	r	Industry review of draft: Chapter 5, "Magnetics", *Measurements for Competitiveness in Electronics*, First Edition.
1993	a	Chapter 5, "Magnetics", *Measurements for Competitiveness in Electronics*, First Edition.

Superconductors

1990	a	Chapter 3, "Superconductors", *Emerging Technologies in Electronics*, Second Edition.
1993	a	Chapter 6, "Superconductors", *Measurements for Competitiveness in Electronics*, First Edition.
1993	i	Robert L. Peterson, "An Analysis of the Impact on U.S. Industry of the NIST/Boulder Superconductivity Programs: An Interim Study", Report No. NISTIR 5012 (November 1993).

Low Frequency

1995	a	Low-frequency measurement needs, to be completed in 1995.

Microwaves

1990	a	Chapter 8, "Microwaves", *Emerging Technologies in Electronics*, Second Edition.
1990	r	Industry review: Chapter 8, "Microwaves", *Emerging Technologies in Electronics*, Second Edition.
1993	a	Chapter 7, "Microwaves", *Measurements for Competitiveness in Electronics*, First Edition.

Lasers

1990	a	Chapter 7, "Lasers", *Emerging Technologies in Electronics*, Second Edition.
1991	r	Industry review: Chapter 7, "Lasers", *Emerging Technologies in Electronics*, Second Edition.
1993	a	Chapter 8, "Lasers", *Measurements for Competitiveness in Electronics*, First Edition.
1993	r	Industry review: Chapter 8, "Lasers", *Measurements for Competitiveness in Electronics*, First Edition.

Optical-Fiber Communications

1990	a	Chapter 5, "Lightwaves: Optical-Fiber Communications", *Emerging Technologies in Electronics*, Second Edition.

1992	i	Albert N. Link, *Economic Impact of NIST-Supported Standards for the U.S. Optical Fiber Industry: 1981 - Present* (February 1992).
1993	a	Chapter 9, "Optical-Fiber Communications", *Measurements for Competitiveness in Electronics*, First Edition.
1993	r	Industry review: Chapter 9, "Optical-Fiber Communications", *Measurements for Competitiveness in Electronics*, First Edition.

Optical-Fiber Sensors

1990	a	Chapter 6, "Optical-Fiber Sensors", *Emerging Technologies in Electronics*, Second Edition.
1993	a	Chapter 10, "Optical-Fiber Sensors", *Measurements for Competitiveness in Electronics*, First Edition.
1993	r	Industry review: Chapter 10, "Optical-Fiber Sensors", *Measurements for Competitiveness in Electronics*, First Edition.

Optical Information Storage

1995	a	Optical information storage measurement needs assessment, to be completed in 1995.

Computers

1994	a	Computers measurement needs assessment, to be completed in 1994.

Video

1990	a	Chapter 9, "Video Technology", *Emerging Technologies in Electronics*, Second Edition.
1993	a	Chapter 11, "Video", *Measurements for Competitiveness in Electronics*, First Edition.
1993	r	Industry review of draft: Chapter 11, "Video", *Measurements for Competitiveness in Electronics*, First Edition.

Power

1994	i	John D. Ramboz, *Economic and Technical Impacts and Value of the NIST Calibration Services for Electrical Power and Energy*, to be completed in 1994.
1995	a	Power measurement needs assessment, to be completed in 1995.

Electromagnetic Compatibility

1990	a	Chapter 10, "Challenges to Emerging Technologies: Electromagnetic Compatibility", *Emerging Technologies in Electronics*, Second Edition.
1991	r	Industry review: Chapter 10, "Challenges to Emerging Technologies: Electromagnetic Compatibility", *Emerging Technologies in Electronics*, Second Edition.
1991	i	Albert N. Link, *Estimates of Economic Impact of NIST Research in Electromagnetic Compatibility/Interference (EMC/EMI) Metrology* (December 1991).
1993	r	Industry review of draft of Chapter 12, "Electromagnetic Compatibility", *Measurements for Competitiveness in Electronics*, First Edition.
1993	a	Chapter 12, "Electromagnetic Compatibility", *Measurements for Competitiveness in Electronics*, First Edition.

Electronic Data Exchange

1995	a	Electronic data exchange needs assessment, to be completed in 1995.

National Electrical Standards

1995	a	To be addressed as part of the low-frequency measurement needs assessment in 1995.

31. *Semiconductor Materials Characterization: Present Status and Future Needs*, a workshop on measurement needs to be conducted on October 24-28, 1994 in Gaithersburg, MD, sponsored by the National Institute of Standards and Technology, the Advanced Research Projects Agency, and other organizations.

32. The social rate of return is a means of placing on a comparable basis the costs and benefits of projects with different periods of costs (during development) and different periods of benefits (during use of project results). The technique considers the time value of money. The social rate of return increases as the benefits increase relative to the costs. The social rate of return is very much like an annualized return on an investment. The social rate of return may be compared with the return available from other investments, such as placing the same amount of money in a savings account, to determine the desirability of the given investment. The benefits equal the costs if the social rate of return is equal to the opportunity cost of capital.

The social rate of return is calculated by a method similar to that used for the private rate of return. However, the social rate of return considers the total costs to society and the total benefits to society. In contrast, the private rate of return considers only the costs to the firm and the benefits to the firm, even if there are additional costs and benefits to society.

33. Edwin Mansfield, John Rapoport, Anthony Romeo, Samuel Wagner, and George Beardsley, "Social and Private Rates of Return from Industrial Innovations", *Quarterly Journal of Economics*, Vol. 91, p. 233 (May 1977). J. G. Tewksbury, M. S. Crandall, and W. E. Crane, "Measuring the Societal Benefits of Innovation", *Science*, Vol. 209, p. 659 (August 8, 1993).

34. Dr. Allan Bromley, *Research and Development in the President's FY 1992 Budget, Testimony of Dr. Allan Bromley, Director, Office of Science and Technology Policy, Before the Committee on Science, Space, and Technology, House of Representatives*, p. 2 (February 20, 1991).

35. Albert N. Link, *Economic Impact on the U.S. Semiconductor Industry of NIST Research in Electromigration*, pp. ii, 1, and 30-39 (January 1992).

36. Albert N. Link, *Economic Impact of NIST-Supported Standards for the U.S. Optical Fiber Industry: 1981 - Present*, p. i-ii, 16-17, and 35-39 (February 1992).

37. Albert N. Link, *Estimates of Economic Impact of NIST Research in Electromagnetic Compatibility/Interference (EMC/EMI) Metrology*, p. 12-18 and 20 (December 1991).

38. From World Business Publications, as published in *Superconductor Week* (February 27, 1989).

39. Robert L. Peterson, "An Analysis of the Impact on U.S. Industry of the NIST/Boulder Superconductivity Programs: An Interim Study", Report No. NISTIR 5012, p. 5 (November 1993).