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ELECTRONICS AND ELECTRICAL ENGINEERING LABORATORY

1991 STRATEGIC PLAN

Supporting Technology for U.S. Competitiveness in Electronics

Prepared by the Electronics and Electrical Engineering Laboratory

U.S. DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
Electronics and Electrical Engineering Laboratory
Gaithersburg, MD 20899

November 1991

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Robert A. Mosbacher, Secretary
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PREFACE

This document is the strategic plan of the Electronics and Electrical Engineering Laboratory (EEEL) for meeting critical measurement needs of the U.S. electronics industry. A special emphasis has been given to measurement development required for improved competitiveness. The plan was developed in collaboration with other NIST Laboratories, industry, and government agencies.

The plan outlines the broad strategic directions of a program responsive to measurement needs arising across many fields of electronics. The plan also describes, as examples, specific strategic directions for four of the fields: semiconductors, microwaves, optical-fiber communications, and video. The plan relates the driving forces for these strategic directions to the role that measurements play in improving competitiveness. The organizations benefiting from the program are described, and examples of program impact are provided.

EEEL's budget for this program was $38 million for fiscal year 1991. Fifty-two percent of this amount was provided by direct appropriation from the Congress. Thirty-nine percent was provided by other agencies. The remaining nine percent was received as a reimbursement for calibration and related measurement services provided to individual industrial organizations and Federal agencies to assure the accuracy of their measurement systems. An additional $1.4 million was transferred by EEEL to other NIST Laboratories for support of the overall program. Sixty-eight percent of this sum was provided by direct appropriation and the remainder by other agencies.

The staff of EEEL numbered 352 in FY 1991, of which 305 were full-time permanent employees. In addition, the Laboratory hosted 45 guest scientists and industrial research associates during the year.

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

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TABLE OF CONTENTS

SUMMARY ix

I. INTRODUCTION 1

Scope of Plan 1
Fields Addressed 1
Relationships Among Fields 2
Associating Projects With Fields 2
Services of the Fields 2

II. MISSION 3

National Goals 3
Customers 3
Deliverables 3
Measurement capability 4
Measured materials reference data 4
Techniques for analyzing measured data 4
Other generic technology and fundamental research 4
Means of Delivery 4

III. RESOURCES AND PLANNING 5

Resources 5
Planning 5

IV. DRIVING FORCES FOR STRATEGIC DIRECTIONS 6

V. STRATEGIC DIRECTIONS ACROSS FIELDS 7

Higher Accuracy/Sensitivity 7
Quantum Phenomena 7
Higher Frequencies 8
Digital Techniques 8
Monolithic Integration 8
Microdimensional Electromagnetic Measurements 8
Automated Systems 9
Energy Efficiency 9
Compatibility 9

VI. STRATEGIC DIRECTIONS WITHIN FIELDS 9

Plans for Growth 9

SEMICONDUCTORS 10

Importance of Field 10
Trends 11
Marketplace 10
Technical 10
Strategic Directions 12
Strategy 12
Implementation Examples 13

MICROWAVES

Importance of Field 13
Trends 14
Marketplace 14
Technical 14
Strategic Directions 15
Strategy 15
Implementation Examples 15

OPTICAL-FIBER COMMUNICATIONS 16

Importance of Field 16
Trends 16
Marketplace 16
Technical 17
Strategic Directions 17
Strategy 17
Implementation Examples 17

VIDEO

Importance of Field 18
Trends 19
Marketplace 19
Technical 19
Strategic Directions 20
Strategy 20
Implementation Examples 21

VII. FACILITIES 21

General Facilities Concerns 21
Major Facilities Plans 21

VIII. CUSTOMERS 22

Direct Customers 22
Indirect Customers 23
Future Directions 23

IX. IMPACT 24

Semiconductors 24
Entire Program and Selected Projects 24
Microwaves 24
Near-Field Scanning Measurements of Antennas Project 25
Lightwaves: Optical-Fiber Communications
Optical-Fibers Project 25
Optical-Fiber Communications Program 25
Power Networks 25
Watthour Meter Calibration Project 25
Electromagnetic Compatibility 25
Crawford Cell Project

LIST OF TABLES

1 Fields of Electronics 1
2 Relationships Among Fields 2
3 Services 2
4 Mission 3
5 Means of Delivery 4
6 Strengths and Weaknesses 5
7 Planning Documents 5
8 Buyer's Demands 6
9 Demands for Product Characteristics 6
10 Manufacturer's Challenges - I 7
11 Manufacturer's Challenges - II 7
12 Plans for Growth in Program Sizes 9
13 Semiconductors 12
14 Microwaves 15
15 Optical-Fiber Communications 17
16 Video 20
17 Facilities Concerns 21
18 Major Facilities Plans 21
19 Customer Organizations by Type 22
20 Coverage of Fortune 500 by Category 22
21 Industrial Customer Organizations by Size 23
22 Forces Shaping Customer Base 23
23 Impact Study Traits 24

SUMMARY

The U.S. electronics industry plays a critical role in the U.S. economy. Virtually every study of emerging or critical technologies cites electronics as a key technology. Among U.S. manufacturing industries, the electronics industry is the largest employer (1.94 million) and is a close second in shipments ($266 billion) to the chemical industry (1990). U.S. competitiveness in many fields of electronics has been declining. The experts agree that a key challenge for recovery is achieving *rapid commercialization of new technology*. Rapid commercialization requires outstanding performance from manufacturers in every step required to put a product into service to the buyer. The key steps are highly measurement intensive and have outstripped available measurement support.

Conclusions and Action Plan

Measurement Focus. EEEL is responding and has concluded that it can make its greatest contribution to competitiveness through improved measurement support for U.S. industry. There are several reasons. Measurement capability has an extraordinary impact on every step that a manufacturer must complete to put a product into service to the buyer: research and development, manufacturing, marketplace exchange, and after-sales support. Measurement capability is a critical factor in the success of new management strategies aimed at improving competitiveness, such as total-quality management, flexible manufacturing, and concurrent engineering. NIST has a unique responsibility to meet critical national measurement needs beyond the reach of individual companies or other government agencies. NIST has the special characteristics required to develop new measurement capability and to achieve its broad acceptance: strong measurement-research base, impartiality, and international reputation in metrology.

Expanded Programs. To meet national measurement needs in electronics, EEEL must greatly expand its present measurement programs. EEEL has identified fifteen fields of electronics which reflect the principal areas of need: semiconductors, superconductors, magnetics, microwaves, lightwaves (including optical-fiber communications, optical information storage, optical signal processing/computing, and optical-fiber sensors), power networks, video, electromagnetic compatibility, complex-system description, and complex-system testing (including high-efficiency testing and high-accuracy testing). EEEL currently has programmatic activity in thirteen of these fields (all but optical signal processing/computing and optical information storage). EEEL is pursuing the additional resources required for expanded programs, with emphasis on directly appropriated resources. EEEL continues to optimize the use of its present resources.

Strengthened Planning. EEEL is studying industry's measurement requirements with the goal of producing full assessments in all fifteen fields within the next two years. At the present time, EEEL has completed and published either comprehensive or preliminary assessments for nine of the fifteen fields. The assessments are developed in close consultation with NIST's direct customers, which include small companies, large corporations, government agencies, and many other organizations. EEEL continues to evaluate the effectiveness of its programs through impact studies.

NIST-Wide Collaboration. EEEL's assessments of the measurement requirements of the electronics industry have indicated the need for an NIST-wide response for many of the fields of electronics, since some key problems arise from non-electronic technologies. Thus EEEL is increasingly seeking collaboration with other NIST Laboratories for implementation. EEEL has established collaboration in six of fifteen fields known to need NIST measurement support. All seven of the other NIST Laboratories are represented, and 51 collaborative efforts of varying sizes are in place.

Strategic Directions Across Fields of Electronics. EEEL is pursuing nine key directions in measurement support that are responsive to needs that cut across the many fields of electronics: *higher accuracy/sensitivity* to support higher performance levels, improved quality control, and more successful technology transfer; *quantum phenomena* as the basis for ultimate reference standards for electronic quantities; *higher frequencies,* with emphasis on optical and microwave frequencies, for higher information capacity, faster speeds, and higher resolution in electronic applications; *digital techniques* for reduced sensitivity to noise and improved signal processing to gigabit-per-second speeds; *monolithic integration* in multiple electronic fields for improved functionality per unit cost and for improved quality control and performance; *microdimensional electromagnetic measurements* for realization of the full potential of small devices; *automated electronic systems* for improved manufacturing quality at reduced cost; *energy efficiency* in electrical systems and in electronic circuits where heating can limit device density and lifetime; and *compatibility* for resolving electromagnetic interference problems, for dual-technology products (e.g., microwave/lightwave), and for precision interfaces in optoelectronic systems generally.

Strategic Directions Within Fields of Electronics. EEEL plans to build its largest programs in four of the fifteen fields. The key strategic directions for the four follow. Three of the four are collaborative with other parts of NIST. For them NIST, rather than EEEL alone, is listed as performer.

Semiconductors: NIST will focus principally on measurement support for the manufacture of semiconductor integrated circuits, which account for 83 percent of the international semiconductor-device market. The goal is improved support for more complex circuits, which require smaller devices, higher materials purity, and better manufacturing processes, process diagnostics, and process control. A key long-term aim will be real-time measurements for active process control.

Microwaves: EEEL will focus on measurement support for the development of microwave integrated circuits and integrated antennas, with emphasis on higher performance, higher frequencies, digital techniques, and a merger with optical technologies. The goal is to provide measurement capability that industry needs to meet demands for a growing diversity of commercial and government applications of microwave electronics for communications, signal processing and computing, radar and navigation, and sensing and manufacturing. Examples include intelligent vehicle and highway systems (auto-collision and traffic-light radar, and pin-point vehicle navigation) and advanced communications (mobile and international digital networks, and worldwide portable telephones).

Optical-fiber communications: NIST will provide measurement capability to support optical fibers and accompanying optoelectronic components in optical-fiber communications systems. The approach is to support first those components needed for the most fundamental systems: fibers, sources, detectors, and waveguides. Then, support will be expanded to provide for components and technologies required for more sophisticated systems that offer higher performance levels, integrated structures, and network capability: modulators, hybrid and integrated-optic circuits, amplifiers, multiplexing, switching, and coherent communications, among others.

Video: NIST will address all five supporting technologies: vision (image generation), signal processing, transmission, information storage, and displays. Early efforts will focus on signal processing and transmission with emphasis on (1) methods for evaluating algorithms that reduce (compress) the data stored or transmitted, and (2) characterization and standards information for interfaces between high-speed equipment and transmission networks. Measurement support for high-density magnetic information storage will be addressed by a separate program on magnetics because of its applicability beyond video. A key future thrust will be measurement support for displays.

ELECTRONICS AND ELECTRICAL ENGINEERING LABORATORY
Strategic Plan

I. INTRODUCTION

The Electronics and Electrical Engineering Laboratory, working in concert with other NIST Laboratories, is providing supporting technology that is critical to the competitiveness of the U.S. electronics industry. Among U.S. manufacturing industries, the electronics industry is the largest employer (1.94 million) and is a close second in shipments ($266 billion) to the chemical industry (1990).[1] The electronics industry exerts extraordinary influence on the performance of every other U.S. industry and is advancing at an unprecedented rate as new technologies emerge. In the process, the electronics industry is outstripping supporting measurement technology, seriously impairing U.S. competitiveness.

Table 1: FIELDS OF ELECTRONICS

Fields	
semiconductors	
high-density silicon integration	c
compound-semiconductor integration	c
superconductors	
low temperature	
high temperature	c
magnetics	
high-density magnetic information storage	c
magnetic sensing	
advanced materials	
microwaves	
individual components	
integrated components	
lightwaves	
lasers	
optical-fiber communications	c
high-density optical information storage	f
optical signal processing and computing	f
optical-fiber sensors	
computers	
information networks	
power networks	
power transmission	
power control	
video	
high-resolution vision	f
high-speed signal processing	c
high-data-rate transmission	
high-density information storage	
high-resolution displays	f
Cross-Cutting Fields	
electromagnetic compatibility	
complex-system description	c
complex-system testing	
high efficiency	
high accuracy	

c = collaborative with other NIST Laboratories
f = future EEEL support anticipated

Scope of Plan

This plan addresses the measurement support that U.S. industry needs from NIST in those fields of electronics that EEEL has analyzed in depth. The plan presents EEEL's strategy for the full response needed from NIST, no matter which organizational units within NIST may be needed to respond or what the cost. EEEL's role in that response is also presented.

Fields Addressed

The fields of electronics that EEEL has determined as needing NIST support are shown in Table 1. They are principally those containing *emerging technologies*; they are all *critical technologies*. They include electronic, electrical, optical, and magnetic technologies, and combinations of them. Increasingly, these fields mutually depend on one another. They are truly becoming *merging technologies*.

Of the fields in Table 1, there are several that EEEL presently does *not* support but plans to support in the future; they are marked "f". Also, EEEL does not address the architecture and other broader aspects of computers and information networks; they are addressed by the Computer Systems Laboratory. Rather, EEEL contributes support for electronic components only, through its support of the other fields. In the table, several fields are already the subject of formal *collaboration* between EEEL and other NIST Laboratories; those fields are marked "c". All seven of the other NIST Laboratories are represented, with 51 collaborative efforts of varying sizes in place.[2] The cross-cutting fields at the bottom of the table address challenges that are common to many of the fields at the top of the table.

Relationships Among Fields

Table 2 shows how the fields from the top of Table 1 relate to each other in terms of *support*. As used here, a supporting field is one that *provides components that are incorporated into the products of another field* (the dependent field). A given field may support some fields and be dependent on others. Support flows in all directions in the table -- a reflection of the fact that the technologies are merging. However, the dominant direction of flow is from the upper-left corner to the lower-right corner, as suggested by the arrows in the table. For example, the semiconductor field is in the upper-left corner because this field is the most supportive of all; that is, semiconductor components are incorporated *in* the products of virtually every other field in the table. The video field is in the lower-right corner because this field is the most dependent of all; its products incorporate components *from* virtually every other field in the table except superconductors and power networks. The fields in the middle row of the table are intermediate. For example, microwave products are dependent on components *from* the semiconductor and magnetic fields (and may soon be dependent on components from the superconductor field). In turn, microwave components are, or will be, incorporated *in* the products of every field to the right and below the microwave field in the table.

Table 2: RELATIONSHIPS AMONG FIELDS

flow of support →

semiconductors	superconductors	magnetics
microwaves	lightwaves	computers
information networks	power networks	video

Associating Projects With Fields

EEEL uses the scheme in Table 2 to associate individual technical projects with one field uniquely. The scheme determines where a given project will appear in EEEL's plans, including this strategic plan, and where it will appear in EEEL's initiatives. For example, an integrated-circuit project that is broadly supportive of applications in many other fields is associated with the *semiconductor* field. However, an integrated-circuit project that is supportive of microwave integrated circuits only is associated with the *microwave* field, even though all microwave integrated circuits are made of semiconductors. Generally speaking, projects are preferentially associated with fields as far to the left and to the top of Table 2 as their breadth of applicability suggests. For this reason, nearly all of the work needed to support high-data-rate transmission for the video field will be associated with the *lightwave* (optical-fiber communications) field or with the *microwave* field because the work is largely generic to other transmission needs as well. However, any transmission project that proves peculiar to video will be associated with the *video* field.

Services of the Fields

In the most general sense, EEEL supports the two principal classes of services provided by the fields of electronics -- *information* and *energy* -- as shown in Table 3. Both classes are reflected in nearly every field in Table 1. For example, lasers generate light for carrying information in optical fibers; lasers also generate light as energy for cutting and welding. Similarly, semiconductors store and manipulate information in computers; they also manipulate energy in power systems (as in ac-to-dc conversion). Other services provided by electronic systems generally reduce to information and energy. For example, electronic systems that are used for the control of virtually every modern manufacturing process perform their tasks by generating and manipulating information and by then delivering energy to appropriate manufacturing devices.

Table 3: SERVICES

Information	Energy
generation	generation
manipulation	manipulation
transfer	transfer
storage	storage
display	use

II. MISSION

EEEL's mission is to serve as the world's best source of fundamental and industrial measurement methods and reference standards of high leverage for the U.S. electronics industry, and to deliver these resources to industry and Government in support of national goals. EEEL views its mission principally in terms of three factors: national goals served, customers served, and deliverables pursued for those customers, as shown in Table 4. The entries under each of the three main headings in Table 4 are in priority order. EEEL addresses all of the elements in the table but distributes its resources to reflect these priorities.

National Goals

EEEL pursues, as its top priority goal, the strengthening of the U.S. economy, primarily through improved competitiveness. EEEL also supports improved Government operations and health and safety by providing needed technical support. For health and safety, EEEL provides both direct support (e.g., electric-fields measurements for biological researchers) and indirect support since virtually every electronic device with a health or safety function is advanced by EEEL's deliverables.

Table 4: MISSION

National Goals
- strengthen U.S. economy
  - improve industry's competitiveness
- improve Government operations
- improve health and safety

Customers
- industry
- government
- educational institutions

Deliverables
- supporting technology
  - measurement capability
    - absolute accuracy
    - reproducibility
  - measured materials reference data
- generic technology
  - techniques for analyzing data
  - *others*
- fundamental research

Customers

EEEL serves industry, other government agencies (Federal, state, and local), and educational institutions. The general public has not been listed as a customer in Table 4 because virtually all of EEEL's services that support the general public are provided through one of the three other customers listed. EEEL serves the research community wherever it is located -- in industry, government agencies, or educational institutions. A characterization of EEEL's customers is contained in section VIII.

Deliverables

EEEL provides deliverables that yield high leverage in achieving the specified national goals and that are consistent with NIST's broad legislated authority. As shown in Table 4, EEEL provides three principal categories of deliverables: supporting technology, generic technology, and fundamental research. EEEL's places its top priority on supporting technology, with a special emphasis on measurement capability. This emphasis reflects a combination of the high leverage of measurement capability on competitiveness, and other key factors (such as NIST's unique role). Leverage, in this case, means the economic impact per dollar of NIST investment. EEEL's emphasis on measurement capability reflects the broad impact of measurements on the *rapid commercialization of new technology*. Rapid commercialization is widely accepted as a key competitiveness challenge of the U.S. electronics industry, as opposed to access to new technology or additional fundamental research. Other agencies, principally NSF, DOD, and DOE, invest billions of dollars in new technology and fundamental research that is supportive of electronics; additional investment by EEEL would be small in comparison. Further, NIST has a unique responsibility to meet critical national measurement needs which cannot be meet by individual companies and other agencies. For the electronics industry, those needs are both vast and urgent.

Measurement capability. EEEL places the highest priority on delivering absolute accuracy, in keeping with NIST's unique role as *the* national reference laboratory for measurements. Absolute accuracy may require a documented measurement method (and/or a special measurement device), a supporting reference standard, and a means of delivery such as a measurement assurance program or a calibration service. EEEL also provides reproducible measurement capability. Virtually every fundamental advance that EEEL makes in measurement capability requires new knowledge and therefore intensive fundamental research. Key generic-technology development is often required to put measurement capability into a deliverable form. Thus EEEL conducts a considerable amount of generic-technology development and fundamental research in direct support of its measurement mission.

Measured materials reference data. EEEL develops reference data on the electronic properties of materials if NIST's special measurement skills are needed for development, or if NIST's evaluation and imprimatur are needed for wide acceptance. However, whenever possible, EEEL prefers to provide industry with measurement capability that industry can use to develop the data for itself, maximizing EEEL's leverage.

Techniques for analyzing measured data. EEEL develops generic technology in the form of techniques for analyzing measured data. Examples include test strategies for complex electronic systems, and expert system analyses for semiconductor process lines. These techniques, together with measurement capability and materials reference data, are EEEL's *measurement-related deliverables.*

Other generic technology and fundamental research. EEEL develops other *generic technology* as well. Examples include complex-systems descriptions to aid automated manufacturing, and process technology for superconducting and semiconducting integrated circuits. EEEL also conducts *fundamental research*, other than that required for its measurement-related deliverables, if targets of unusual opportunity present themselves; usually this research requires measurement capability available only at NIST. A key example is EEEL's work on determining the values of fundamental physical constants, such as the fine-structure constant and the gyromagnetic ratio of the proton.

Table 5: MEANS OF DELIVERY

Communications	FY90
publications	200
software requests	78
talks	263
consultations	1350
visits	325
visitors	890
meetings	
attendees	375
contributors	115
Joint Activities	
standards organizations	
staff participating	48
memberships	90
professional societies	
memberships	200
interlaboratory measurement comparisons	27
cooperative research	111
consortia (incl. forming)	7
research associates	5
guest scientists	58
Paid Services	
custom measurement development	150
standard reference materials	225
calibration services	
tests	3189
customers	404
training courses	16

Means of Delivery

EEEL provides its deliverables by three principal means, as shown in Table 5: communications, joint activities, and paid services. FY 1990 levels of activity are shown in the table. These means of delivery involve regular interactions with industry, government agencies, and universities. The interactions are essential to planning as well as to delivery. Over the past three 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 the staff indicates that the staff has reached capacity in the number of technology-transfer activities that it can handle at its present size.

III. RESOURCES AND PLANNING

Resources

EEEL's strengths and weaknesses are outlined in Table 6. Only the weaknesses will be discussed here; they lie principally in the area of resources. EEEL's greatest challenge, by far, is posed by the growing demands of the electronics industry for NIST's assistance, compared to the level of available funding. The high demand is the result of the large size of the electronics industry and its increasingly measurement-intensive nature. Just the cost of making measurements is a significant part of the cost of manufacturing electronic products, amounting to 20 to 25 percent in the fields for which reports are available. The shortfall in EEEL's funding has given rise to four key consequences: (1) programs are spread thin to meet as many critical national needs as possible; forward-looking research, required for long-term effectiveness, is undertaken at the expense of urgent industrial needs; (2) response to needs is often slow; (3) flexibility in shifting resources is limited; and (4) dependency on funding from other agencies is high (39 percent). While other-agency funding contributes to meeting national needs, it is not as readily focused as direct funding on the full breadth of those needs. Breadth for NIST is essential since NIST is the only agency charged with assisting industry and government across all sectors, not just energy or defense, for example. A further weakness is the shortage of special funding for equipment and facilities, impeding EEEL's effort to maintain leading-edge capability. Facilities needs are discussed further in section VII.

Table 6: STRENGTHS AND WEAKNESSES

Strengths
- staff diversity and quality
- breadth of program coverage
- reputation (credibility, objectivity)
- measurement research base

Weaknesses
- funding relative to industry's needs
  - spread thin
  - slow response
  - limited flexibility
  - dependency on other-agency funding
- special funding for equipment and facilities

EEEL is addressing each of these important weaknesses. To resolve the funding problems, EEEL has been pursuing for many years a number of budget initiatives with some success, both for itself and for collaborating NIST Laboratories. If these initiatives continue to be successful, EEEL will be able to meet additional critical national needs. Also, EEEL will be able to reduce its percentage of funding from other agencies from 39 percent to perhaps 30 percent, while still increasing funding from those agencies in absolute terms. The initiatives will permit more effective funding of forward-looking research. They will also increase the amount of special funding available for equipment and facilities.

Planning

EEEL attaches considerable importance to planning. Key efforts are outlined in Table 7.

Table 7: PLANNING DOCUMENTS

Fields	≤'88	'89	'90	'91	'92
semiconductors	ii	a	a	ria	sa
superconductors	.	a	a	ia	a
magnetics	s	a	a	a	a
microwaves	s	a	a	a	a
lightwaves					
lasers	.	.	a	ra	a
optical-fiber communications	i	a	ia	ia	a
optical information storage	.	.	.	.	a
optical processing/computing	.	.	.	.	a
optical-fiber sensors	.	.	a	a	a
power networks	.	.	.	ia	a
video	.	.	a	a	a
Cross-Cutting Fields					
electromagnetic compatibility	.	.	a	ria	a
complex-system description	.	.	.	.	a
complex-system testing					
high efficiency	.	.	.	.	a
high accuracy	s	.	.	.	a

a = assessment of industry's measurement needs
r = review of measurement needs assessment by industry
s = survey of industry's measurement needs
i = impact study (ii = two studies in one year)

EEEL is developing assessments of industry's measurement needs and is publishing them periodically to obtain feedback from industry and government. The most recent publication is *Emerging Technologies in Electronics and Their Measurement Needs* (February, 1990). The assessments completed through FY 1990, and the new or updated assessments planned for future fiscal years, are marked "a" in Table 7. For selected assessments, EEEL has solicited reviews ("r") by industry experts and has revised the assessments according to their responses. EEEL has also conducted a number of surveys ("s"), employing either questionnaires or coordinated contacts with industry at both technical and managerial levels. Finally, EEEL and the NIST Program Office have conducted a number of impact analyses ("i") to determine how completed work affected industry. Key findings from the impact studies are reported in section IX. This formal set of processes is complemented by regular contacts with industry by all staff members; they gather information on changing measurements needs and on impact.

Table 8: BUYER'S 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*

IV. DRIVING FORCES FOR STRATEGIC DIRECTIONS

Because EEEL's primary goal is improving industry's competitiveness, the driving forces for EEEL's strategic directions can best be understood in a competitiveness context. Ultimately, the buyer determines whether a product is competitive in the marketplace. The buyer's demands are summarized in Table 8. The buyer's demands for desirable *product characteristics* in particular are elaborated with key examples in Table 9. To meet the buyer's demands, the manufacturer must address a wide range of challenges, as outlined in Table 10 and Table 11. Table 10 focuses on the steps that a manufacturer must complete to put a product into service to the buyer. Table 11 focuses on the broad management challenges that a manufacturer must address while completing the steps in Table 10. In all four tables, arrows mark the *measurement-dependent factors*, that is, the factors affected by the level of available measurement capability. The number of arrows reflects the pervasive impact of measurement capability on competitiveness. A detailed discussion of this relationship has been prepared for publication in a separate document.[3]

EEEL responds by providing measurement support that affects virtually every measurement-dependent factor marked in the four tables. In addition, EEEL increasingly provides selected generic-technology support for many of the same factors. More specifically, EEEL supports all four of the categories of manufacturer's challenges in the major headings in Table 10. EEEL's support for *marketplace exchange* has always been strong. EEEL has steadily increased its measurement support for the earlier stages in Table 10, particularly for *manufacturing*. Further, EEEL is increasing its support for generic technology related to the implementation of new management strategies in Table 11. More information is provided in the following two sections.

Table 9: DEMANDS FOR PRODUCT CHARACTERISTICS

Performance
- → higher information capacity
- → higher information fidelity
- → higher information density
- → higher energy efficiency

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

Compatibility
- → improved impedance matching
- → improved physical interfacing
- → reduced electromagnetic interference

V. STRATEGIC DIRECTIONS ACROSS FIELDS

EEEL's strategic directions can be described in two ways: (1) those that cut across the fields of electronics and thus reflect EEEL's response to technical trends in the electronics industry broadly; and (2) those that are specific to individual fields. This section looks at those that cut across the fields; section VI looks at the others.

The strategic directions in this section reflect all fifteen fields of electronics shown in Table 7. These fields exclude only computers and information networks, relative to the fields listed in Table 1, since those two fields are addressed by the Computer Systems Laboratory. EEEL presently has some programmatic activity in all but two of the fifteen fields; the two are optical information storage and optical signal processing/computing.

Each strategic direction in this section supports a large number of the measurement-dependent factors in Table 8, Table 9, Table 10, and Table 11. For each strategic direction below, the discussion names representative measurement-dependent factors and provides implementation examples from EEEL's program.

Table 10: MANUFACTURER'S 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
→	maintenance
→	*cost of support*
→	*speed of support*

Higher Accuracy/Sensitivity

EEEL will pursue major advances in the accuracy and sensitivity of its measurements. Affected are industry's pursuit of higher performance, improved quality control, and more successful technology transfer within companies and between companies in collaborative efforts. Examples from EEEL's program include pursuit of (1) more sensitive measurements to reduce the electronic noise that limits the information capacity of microwave transmission systems, and (2) higher absolute accuracy for measurements needed to transfer semiconductor process technology between facilities.

Quantum Phenomena

As a special dimension of higher accuracy, EEEL will pursue quantum phenomena at the most fundamental level. This effort will support electrical measurements needed for research and development, and it will support future electronic products based on quantum phenomena (e.g., quantum-confinement semiconductor devices). For example, for voltage, the national standard is already based on a quantum phenomenon (the Josephson effect); and the theory is

Table 11: MANUFACTURER'S CHALLENGES - II

	Raise Resources		**Protect Resources**
	capital		intellectual property
	equity		
	debt		
	labor		**Implement New**
	managers		**Management Strategies**
	workers	→	total-quality management
	matériel	→	flexible manufacturing
→	equipment		collaboration outside
→	supplies	→	cooperative development
	technology	→	technology transfer
	supporting		collaboration within
→	measurements	→	teamwork
	generic, other	→	concurrent engineering

well understood. For resistance, EEEL will conduct fundamental research to develop the theory behind the quantum Hall-effect devices that provide the national standard. For electrical current, EEEL will search for quantum phenomena based on electron counting that can provide a national standard to complete the Ohm's Law triad. A key long-term goal is determining if the present definitions of the basic electrical quantities, and possibly mass also, in the International System of Units can be replaced with new definitions based on fundamental constants (electronic charge, Planck's constant, etc.). This replacement would potentially give the nation's laboratories direct access to the fundamental standards and would improve support for fundamental research, enabling, for example, precise tests of physical laws.

Higher Frequencies

EEEL will provide increasing support for higher frequencies. Higher frequencies are needed to provide higher information capacity for communications, higher resolution for radar, and controllable limited range for both communications and radar, among other benefits. For example, EEEL will emphasize support for microwave technology (centimeter to submillimeter) and for lightwave technology, including especially optical-fiber communications and laser technology.

Digital Techniques

EEEL will provide increased support for digital techniques. Digital electronics are an important means of achieving higher information fidelity, since digital techniques can reduce sensitivity to noise in electronic and optical systems. This reduction is particularly important during the transmission and storage of data. For example, EEEL will develop measurement methods for characterizing digital signal quality at gigabit data rates for optical-fiber and microwave transmission systems, including those required for advanced video.

Monolithic Integration

EEEL will provide increased support for monolithic integration. Monolithic integration is essential to achieve increased functionality per unit cost, improved quality control, and, in most cases, improved performance. EEEL will provide measurement support for the development and manufacture of semiconductor integrated circuits, superconductor integrated circuits, microwave integrated circuits, and optoelectronic integrated circuits. This support will further research, development, and manufacturing. EEEL will also contribute to generic technology needed for process development. A key long-term goal is the development of non-contacting, non-interfering optical measurement methods for determining internal circuit parameters. Another long-term goal is the development of measurement methods for real-time control of manufacturing processes, essential to flexible manufacturing and zero-defects manufacturing.

Microdimensional Electromagnetic Measurements

EEEL will increase its emphasis on microdimensional measurements in electromagnetic environments. These measurements are needed to support higher information density during storage, monolithic integration as discussed above, and other goals. For example, EEEL will develop measurements for microscopic magnetic domains for high-density magnetic information storage. Further in the future, support will be provided for high-density optical information storage.

Automated Systems

EEEL will provide increased support for automated electronic systems, including those used for manufacturing and testing, to reduce manufacturing costs and improve quality control. For example, for testing, EEEL will develop sophisticated strategies for selecting small sets of tests that are sufficient for characterizing complex electronic products that presently require thousands of tests in the absence of such strategies. For manufacturing, EEEL will contribute to the development of standardized descriptions of complex electronic systems that will reduce the cost of automated design, manufacturing, and support (PDES/STEP).[4] Work in these areas, among others, supports industrial implementation of new management strategies, such as concurrent engineering and flexible manufacturing.

Energy Efficiency

EEEL will pursue measurement support for improved energy efficiency in electronic systems broadly. For example, EEEL will pursue measurements to reduce losses in magnetic, insulating, semiconducting, superconducting, and optoelectronic materials. Energy efficiency is important to nearly all applications of electronic components, such as superconducting wire for electromagnets, semiconducting power devices for electric utilities, and semiconducting and superconducting integrated circuits in which heating can limit device density.

Table 12: PLANS FOR GROWTH IN PROGRAM SIZES

Fields	Present	Planned
semiconductors	m	l
superconductors	s	m
magnetics	s	l
microwaves	s	l
lightwaves		
lasers	s	m
optical-fiber communications	s	l
optical information storage	-	*
optical processing/computing	-	*
optical-fiber sensors	s	s
power networks	s	*
video	s	l
Cross-Cutting Fields		
electromagnetic compatibility	s	m
complex-system description	s	*
complex-system testing		
high efficiency	s	*
high accuracy	s	*

s = small m = medium l = large
* = under study

Compatibility

EEEL will develop a wide range of measurements to support improved compatibility in electronic products. For example, EEEL will develop special measurement support for the resolution of electromagnetic compatibility problems that are critical to gaining access to domestic and international markets. EEEL will provide measurement support for electrical/optical interfaces to permit emergence of dual-technology components, such as microwave/lightwave components for optical-fiber communications and microwave antennas. EEEL will also provide measurement support for some precision physical interfaces, such as fiber-to-fiber connections in optical-fiber communications systems.

VI. STRATEGIC DIRECTIONS WITHIN FIELDS

Plans for Growth

EEEL is developing expanded, or new, programs to address all fifteen fields of electronics shown in Table 12, including two not presently addressed at all: optical information storage and optical signal processing/computing. However, EEEL's present programs are many times smaller than needed to provide full measurement support for U.S. industry. Table 12 provides a relative measure of the *present* size of each of the programs and of the *planned* size needed to meet industry's needs. The relative sizes reflect directly appropriated NIST-wide resources. Funding from other agencies for assistance to their programs is not reflected.

EEEL will seek increased resources, principally through budget initiatives and partly through increased funding from other agencies. EEEL is developing and improving its assessments of industry's measurement needs as the basis for effective planning for these programs. Fields marked with a star (*) in Table 12 are those for which plans for meeting expanding measurement requirements have not yet been completed. A more detailed account of the status of EEEL's planning was provided in Table 7.

Of the fifteen fields in Table 12, four have been selected for discussion below: semiconductors, microwaves, optical-fiber communications, and video. These four fields represent key technologies underlying, or driving, every one of the three high-volume market areas identified as essential to U.S. competitiveness by the National Advisory Committee on Semiconductors (NACS): broadband communications, displays, and intelligent vehicle and highway systems.[5] The four fields are also supportive of the broader range of technologies identified by the Council on Competitiveness as critical to "U.S. productivity, economic growth and competitiveness during the decade ahead."[6] EEEL plans to build its largest programs in these four fields from among the fifteen. The measurement needs of these fields (and five others) have been studied in some detail, and the findings have been published.[7] According to the characterization in Table 2, the four fields represent three different degrees of support for the other fields of electronics: one highly *supportive* field (semiconductors), two *intermediate* fields (microwaves, optical fibers), and one highly *dependent* field (video). The four fields also represent both mature EEEL planning (semiconductors, microwaves, and optical fibers) and developing planning (video).

For each of the four fields, the measurement support needed from NIST is described below at the full level of industry's need, whatever the present level of EEEL's or NIST's resources, and whichever NIST organization is needed to respond. For each field, an accompanying table shows the structure for the planned work. Within each table, annotations have been placed next to each element of the work to indicate if that element is *partially* ("p") or *fully* ("f") funded at the present time. Additional annotations indicate whether *EEEL* ("E"), an *Other* ("O") NIST Laboratory, or a combination of both, will address the element, as the required resources become available. Three of the four fields are addressed collaboratively with other NIST Laboratories.

SEMICONDUCTORS

Importance of Field

Semiconductors are the single most important field of electronics. Most of the nation's $266 billion in annual shipments of electronic products is based on semiconductors. Silicon semiconductors and compound semiconductors (those containing two or more elements) provide the basis for electronic devices and optoelectronic devices. Compound semiconductors are especially important to optoelectronic devices because they can generate light. Gallium arsenide is the most commonly used compound-semiconductor material.

World semiconductor markets are huge. As of 1989 the world market was $71 billion for semiconductor devices, $9.5 billion for semiconductor manufacturing equipment, and $9.4 billion for the materials used in the manufacture of semiconductor devices. The U.S. produced $29 billion of semiconductor devices, or 42 percent of the world market. Japan produced $33 billion of semiconductor devices, or 46 percent of the world market. The U.S. produced $4.5 billion of semiconductor manufacturing equipment, or 48 percent of the world market.[8]

Of the world market for semiconductor devices, 83 percent is in integrated circuits, 13 percent is in discrete (individual) electronic devices, such as transistors and diodes, and the remaining 4 percent is in optoelectronic devices. Understandably, integrated circuits are the dominant focus here. Nearly all integrated circuits are made on flat slices of silicon (wafers) by forming as many as 20 layers of semiconductor, insulating, and conducting materials. The layers are interconnected laterally and vertically and contain feature sizes as small as several tenths of a micrometer (about 1/100 the diameter of a human hair). The manufacturing process can require 500 steps, all of which must be performed successfully for the final product to work, placing extraordinary demands on quality control at every step.

Trends

Marketplace. The world semiconductor market is experiencing *intense international competition.* Although U.S. production of semiconductor devices grew at an average annual rate of 16 percent from 1985 to 1989, the U.S. has been *losing market share* in every one of the three key product categories: (1) For semiconductor devices, the U.S. lost 11 percentage points in the world market from 1985 to 1989, falling from 53 to 42 percent. Europe lost nearly 3 percentage points over the same period. Japan and the rest of the world have been the gainers.[9] (2) For semiconductor manufacturing equipment, the U.S. share dropped from 61 percent in 1985 to 48 percent in 1989 and continues to decline. Over the same period, Japan gained from 30 to 41 percent.[10] (3) For silicon materials, the U.S. share dropped from 42 percent in 1985 to only 7 percent in 1989; Japan gained from 23 to 65 percent; Germany was second with 29 percent in 1989.[11]

At the same time *capital costs for new plant and equipment have been soaring*, presenting formidable barriers to marketplace entry; a modern semiconductor manufacturing facility now costs $500 million, and facilities costing $1 billion are foreseeable. To recover development costs, manufacturers struggle to be *first to market* so that they can benefit from high initial pricing. Further, to remain competitive, manufacturers must maintain about *four generations of devices under development* at any one time, staggered in time. This approach is necessary to meet market requirements for new products every three to four years in the face of ten-year development cycles for each. All of these pressures place a tremendous premium on the effectiveness and efficiency of product design and manufacturing processes. The U.S. competitiveness problem arises principally from *shortcomings in manufacturing*, reflected in such factors as time to market, manufacturing quality, and manufacturing cost. In comparison, U.S. capabilities in product design are broadly competitive.

Technical. The key technical trends are closely interrelated. They reflect industry's pursuit of higher functionality per unit cost for more competitive integrated circuits. Higher functionality per unit cost is accomplished by making *more complex circuits* with *smaller dimensions.* Key examples include multi-megabit memory chips and sophisticated microprocessors. Smaller dimensions (below 1 micrometer) are important to faster performance as well as to increased complexity. Smaller sizes require better control of *dimensions.* They also require better control of *materials purity*; impurity levels as low as 10 parts per billion are sometimes required; and particulates, which look larger to smaller circuit elements, must be carefully limited. The smaller circuits must have smaller active devices (transistors) which, because of their reduced size, exhibit different physical behavior and thus require *new device designs*. More complex circuits also require development of more sophisticated *circuit designs* and *manufacturing processes* to implement those designs. The success of the new manufacturing processes increasingly depends on high levels of *automation* to maintain control of quality and to minimize the presence of contamination unavoidably introduced by the presence of people. Automation in turn requires sophisticated *methods for diagnosing process performance*. Automation also requires high quality *input data for process control*, principally in the form of measurements made during processing, and reference materials data.

Strategic Directions

Strategy. EEEL and collaborating NIST Laboratories have planned a program that is responsive to key infrastructure needs of the semiconductor industry. The program requires skills from throughout NIST. The program focuses principally on measurement development but also requires selected generic-technology development and selected basic research beyond that required for measurement development. The program is outlined in Table 13. EEEL is contributing in many key areas and plans to expand this NIST-wide program to become the largest for any of the fields of electronics addressed by EEEL. NIST will support *dimensional* measurements, stressing the width of circuit features in integrated circuits, the registration (alignment) of successive layers during processing, and the flatness of the wafers on which integrated circuits are made; key emphases will be placed on electrical, optical (including ultra-violet), and electron-beam techniques. NIST will develop improved measurements for *materials purity* in process gases, in process liquids, on surfaces, and in semiconductor materials. NIST will provide improved measurements for device characterization and will conduct basic research on the physics of semiconductor devices to support improved industrial *device design* for silicon and compound semiconductors. At the next level, *circuit design*, where the industry is already strong, no urgent needs that NIST should address have surfaced. NIST will support improved *process development* for integrated circuits by developing measurements and characterizations for processes such as etching (removal of material) and deposition (addition of material), for interfaces between materials or layers, and for evaluating x-ray lithography (photographic-like imaging) for feature sizes below 0.2 micrometers. NIST will support improved design of the protective "packages" (enclosures) in which integrated circuits are permanently mounted by providing performance measurements as well as reference data for the properties of the metals, ceramics, and polymers employed. To support *process diagnostics*, NIST will provide empirical techniques for analyzing process data to determine the corrective action needed to restore proper process performance. The techniques will employ artificial intelligence concepts (expert systems,

Table 13: SEMICONDUCTORS

		$	Labs
Dimensionality			
widths	*1 dimensional*	p	E,O
registration	*2 dimensional*	p	E,O
flatness	*3 dimensional*	-	O
Materials Purity			
gases		-	O
liquids		-	O
solids			
surfaces		p	O
semiconductors		p	E,O
Device-Design Support			
device physics		p	E
device characterization		p	E
Process-Development Support			
integrated circuits			
etching		-	E,O
deposition		p	E,O
interfaces		p	E,O
lithography		p	E
packaging		p	E,O
Process-Diagnostics Methods			
empirical techniques		p	E
analytical process models		-	E
Process-Control Support			
measurements			
off-line/in-line		p	E,O
in-situ		p	E,O
real-time		-	E
reference data		p	E,O
reference standards		p	E,O
Manufacturing Management			
information architecture		-	O

f = fully funded   E = EEEL
p = partially funded   O = Other Lab(s)

neural networks, machine learning). As a longer term goal, sophisticated analytical process models will be developed to provide more exacting diagnoses of process difficulties; the models will contribute to process development as well. To support *process control*, NIST will provide a broad range of new measurement methods and reference materials data, which will also serve process development. The measurement methods will include both "off-line" and "in-line" methods, which interrupt processing, and the newer "in-situ" and "real-time" measurement methods, which do not. The real-time measurements are a key long-term goal of the program. They are the most difficult to develop, but they are powerful tools for quality control. They are conducted inside processing equipment, while a process step is being completed, and in time to correct deviations that would otherwise impair quality. Finally, as a long-term goal, NIST will develop a standardized architecture for the technical information that must be maintained for the successful operation of all aspects of a semiconductor manufacturing facility. This architecture is needed to provide an interface to the highly efficient PDES/STEP approaches, described in section V under "Automated Systems". In much of the measurement work described above, NIST will pursue absolute accuracy of measurements, not just reproducibility, so that successful process technology can be transferred from one facility to another, not just maintained stable in a given facility.

Implementation Examples. For dimensional measurements, NIST will develop a dimensional reference standard, calibrated with an electron beam, to support measurements of features as small as 0.3 micrometer. For materials purity, NIST will develop measurements for water vapor, as a contaminant in process gases, with a sensitivity better than 1 part per million and possibly as good as 10 parts per billion. To support device design, NIST will calculate and measure the mobilities (ease of movement) of the carriers of electronic charge as a function of the direction of movement in layered structures. To support the development of improved packages, NIST will provide measurement techniques for the properties of metal-ceramic interfaces, such as bond strength. For process-diagnostics methods, NIST will develop artificial-intelligence techniques for evaluating the performance of processes in replicating submicrometer features. For process-control support, NIST will develop real-time measurement methods for process parameters influencing reliability.

MICROWAVES

Importance of Field

Microwave technology is the electronic technology of *speed* and *mobility*. Electronic components, including new computer chips, will increasingly employ microwave technology to operate faster. Electronic systems will increasingly employ microwave technology to communicate with, and detect, subjects in motion. Microwave frequencies range from 1 to 1000 gigahertz. They include centimeter, millimeter, and sub-millimeter waves.

The microwave equipment industry is enormous. Within the electronics industry, microwave equipment is the second largest segment of equipment shipments, exceeded only by computers plus their peripherals. For 1989, U.S. shipments of microwave equipment are estimated at $36 billion, about one-seventh of U.S. shipments of all electronic equipment, systems, and components. Worldwide shipments of microwave equipment are likely twice this size and can be expected to approach $100 billion per year in the near term.[12]

U.S. shipments for commercial and non-defense Government applications appear to exceed those for defense applications, which also continue to be highly important.[13] Expanding applications of microwave technology fall into four principal categories, as shown below. They are closely tied to critical national priorities. Even individual applications have enormous potential markets.

Communications: expanded personal, corporate, and mobile communications, including digital pocket cellular radio telephone systems, interconnected with cable network systems and direct-to-satellite systems for worldwide access; a new worldwide communications network for U.S. embassies (a DOS priority); and direct-broadcast satellites for television.

Signal processing and computing: multiplexing and coherent-detection circuits for realizing the full information capacity of optical-fiber communications systems; signal-processing circuits for high-definition television; and logic and computing circuits for high-speed computers.

Radar and navigation: intelligent vehicle/highway functions, such as (1) automobile radar for collision avoidance, obstacle detection, and backup warning, (2) traffic-light-control radar for "green lights all the way" and phenomenal savings of gasoline and time, and (3) satellite pin-point navigation systems for virtually all vehicles; vision systems for robots; improved automated-landing systems and new on-board wind-shear detection systems for aircraft (a DOT/FAA priority); improved weather radar (a DOC/NOAA priority); and new local radar for vehicle and robot monitoring at industrial sites.

Sensing and manufacturing: continuous remote sensing of environmental changes through the Earth Observing System (an NASA/DOC/NOAA priority); monitoring and real-time control of industrial processing of materials; and heat treating of materials.

Trends

Marketplace. The marketplace is experiencing a *major expansion in the diversity of commercial and non-defense applications* of microwave technology. The key categories have been outlined above. Further, the changes in the commercial market are stimulating *unprecedented international competition*. The U.S. has long enjoyed dominance of its own domestic market but has made only limited penetration of foreign markets.[14] Now, the race to exploit more advanced microwave technology, particularly in integrated-circuit form, could dramatically change the competitive balance. Integration offers to reduce the cost per function in microwave circuits by 100 times or more. The U.S. must move quickly to keep pace with strong competition emerging abroad, especially in Japan and Europe. Japan is pushing hard to develop microwave integrated circuits for mobile and optical-fiber communications and for direct-broadcast satellites. Europe is pushing hard, too, emphasizing communications and local radar for traffic-light control. The U.S. has reason to take steps to assure that the microwave market is not the next electronics market lost to foreign competition.

Technical. Microwave technology, already sophisticated, is becoming much more so. *Integration* is being introduced to cut costs and increase performance. *Higher frequencies* (above 30 gigahertz) are being opened to provide key capabilities: more spectrum; increased information-handling capacity; smaller antennas; and controllable limited range for local communications and radar. *Higher performance levels* in virtually all critical parameters are being pursued. *Digital techniques* are being introduced to serve multiple aims, such as reduced sensitivity to noise and increased information capacity (e.g., data compression). *Optical and microwave technologies* are being merged to provide each with the power of the other. For example, microwave signal-processing electronics are key components for optical-fiber communications systems with higher information capacity.

Strategic Directions

Strategy. The advances required for improved competitiveness in microwave products cannot be realized without dramatic progress in measurement support. EEEL's response is the expanded program outlined in Table 14. The program focuses on advanced measurement support for high-performance miniature individual (discrete) components, integrated components, and integrated antennas, including components incorporating optical technology. Attention will focus first on the lower frequencies of 1-100 gigahertz where most near-term applications are arising. Further work will address the higher frequencies of 100-1000 gigahertz where the highest information capacity is obtained and where quasi-optical behavior can be exploited. Central to the program will be measurement support for resolving key problems, including (1) the efficient and controlled transfer of microwave signal power in both circuit components and antennas, and (2) the preservation of signal fidelity during signal transfer at gigabit-per-second data rates. Central also will be measurements and reference data for the electromagnetic properties of materials, needed to support industry in designing improved products and in developing automated manufacturing processes. To succeed at providing the required support, EEEL must develop a broad scope of measurement approaches capable of covering three orders of magnitude in frequency; EEEL must also develop measurement methods that can probe the internal elements of integrated circuits without disturbing the performance characteristics to be measured. Microwave integrated circuits are highly measurement intensive; about 25 percent of the cost of production is in measurements.

Table 14: MICROWAVES

	$	Labs
Individual Components (1-100 GHz)		
electronic devices		
power transfer	p	E
signal fidelity	-	E
materials	p	E
antennas		
performance	p	E
materials	-	E
Integrated Components (1-100 GHz)		
integrated circuits		
power transfer	p	E
signal fidelity	-	E
materials	p	E
integrated antennas		
performance	-	E
element properties	-	E
materials	-	E
Integrated Components (100-1000 GHz)		
integrated circuits	-	E
integrated antennas	-	E

f = fully funded E = EEEL
p = partially funded O = Other Lab

Implementation examples. For individual components, necessary order-of-magnitude improvements in measurement accuracy will be pursued for critical power-transfer quantities (power level, impedance, and attenuation). For integrated components, new non-contacting electro-optical measurement methods will be developed for characterizing circuits without disruption. For both individual and integrated components, special measurements will be developed for signal fidelity (noise and waveshape) in new all-digital implementations of microwave systems. They will support sophisticated techniques such as digital spread-spectrum technology which is being evaluated for handheld networked telephones to provide dramatic increases in information-handling capacity.[15] For antennas, new measurement capability will be developed for sophisticated designs, such as phased-array antennas. They produce beams that can be shaped and steered electronically to serve multiple reception areas dynamically on a time-division basis without physical movement; key applications include direct-broadcast satellites and radar systems of diverse types. New antenna measurement capability will be developed to support integrated antennas; they will incorporate built-in signal transmission, reception, and processing electronics and even optical control elements. The new antenna measurement capability must support antennas ranging in size from many meters in diameter for satellite communications, down to a several centimeters in size for networked telephones and for radar for robot vision, traffic-light control, and auto collision avoidance. New, sophisticated national measurement reference standards will be developed to support the high-performance systems.

OPTICAL-FIBER COMMUNICATIONS

Importance of Field

Optical-fiber communications systems provide the highest information capacity available from a *cable* technology. They complement microwave communications systems which provide the highest information capacity available from a *radio* technology. Optical fibers provide high immunity to interference and high security for data. They transmit information over long distances with extraordinarily low power and extraordinarily low noise.

The economic significance of the optical-fiber communications industry continues to increase. The U.S. market for optical fibers and related opto-electronic components for optical-fiber communications is estimated at $1.4 billion for 1990.[16] The corresponding world market is estimated at $3.8 billion for 1990.[17] The world market for systems is considerably greater and should be in the tens of billions of dollars during the 1990s. Cumulative worldwide investment in undersea lines *alone* is expected to reach $11 billion by the mid-1990s.[18]

Optical-fiber communications systems are essential to national and international network goals for the Integrated Services Digital Network (ISDN) and to national network goals for the National Research and Education Network (NREN). Optical-fiber networks have the potential to create an information-exchange industry that dwarfs anything now known, providing services to industry, government, universities, and individuals for functions in business, publishing, banking, transportation, education, entertainment, and many other areas.

Trends

Marketplace. The first-generation cross-country optical-fiber lines are now installed in the most advanced countries, and the first few trans-oceanic lines are operational. Next will come *higher performance long-distance lines*, including new trans-oceanic lines, and new *local fiber loops for networks* that will provide users with a high-speed optical connection to the long-distance lines. Based on the structure of the present U.S. telephone system, the local fiber loops will eventually account for 90 percent of all telephone links and will therefore represent an enormous market. The networks they form will be interconnected with terrestrial and satellite microwave systems for access to mobile and international users. They will provide services for data, text, audio, and video. The demands that video and high-speed computers, in particular, place on optical-fiber communications systems are major driving forces for higher information capacity. For example, one uncompressed high-definition video signal with 10 times the resolution of present television will require about 1 gigabit per second of information capacity, equivalent to about 125,000 telephone calls (at 8 kilobits per second). This represents the entire capacity of a typical present high-speed optical-fiber line employing a single wavelength.

The lucrative markets for optical-fiber communications systems are promoting intense international competition. The U.S. is competitive in optical fibers, but the Japanese are ahead and moving farther ahead in related opto-electronic components. The Europeans have become strong competitors, too. If the U.S. is to compete, it must develop higher performance components with higher quality and lower cost. Establishing and maintaining U.S. competitiveness in optical-fiber communications is an essential part of U.S. competitiveness in the emerging family of powerful lightwave technologies, including optical information storage, optical signal processing, and optical computing.

Technical. *Higher information capacity* is being pursued by industry through two main approaches: (1) increasing the information carried by a single wavelength in a fiber, and (2) increasing the number of wavelengths transmitted simultaneously in a fiber. Modulators are being developed to impress more information on a single wavelength. Conventional multiplexing is being developed to place as many as 80 wavelengths on a fiber at a time, with 2 wavelengths already implemented in practical systems. Coherent-communications techniques are being researched to provide potentially 1000 wavelengths on a fiber. *Reduced losses* in the strength of the lightwaves passing through optical-fiber communications systems are being pursued in several ways: (1) reduction of losses in the opto-electronic components used with the fibers; (2) reduction of losses in the fibers themselves through development of long-wavelength (halide) fibers; (3) compensation for losses through use of optical amplifiers to restore signal strength. *Network-component development* is being pursued by industry with a focus on fast all-optical switches that guide signals between points of origin and destination. *Integration*, which is a very difficult goal for optoelectronic materials, is being pursued in stages to reduce the size and cost of components for optical-fiber systems.

Strategic Directions

Strategy. Competitiveness in components for optical technology demands extraordinary performance levels that tax current measurement capability. EEEL has defined a comprehensive program for developing the measurement capability that U.S. industry needs. That program is outlined in Table 15. EEEL has begun by developing measurement support for the components most fundamental to optical-fiber communications systems: silica fibers, sources, detectors, and waveguides. EEEL is continuing to provide an increasing scope of measurement capability for these components while expanding its program principally in the areas of modulators and couplers. Next, EEEL will add measurement support for the remaining optoelectronic components and technologies in Table 15 in the order shown. This expansion will provide support for the components required for more sophisticated implementations (higher performance levels, integrated structures, and networks). EEEL will also develop special measurements for the overall performance of the most sophisticated systems, and EEEL will provide measurement support for industrial research toward ultra-low-loss halide (long-wavelength) fibers. Their reduced losses offer potential for increasing the distances between amplifiers to improve system reliability and to reduce system cost. [Note that network architectures and protocols are not addressed here. They are addressed by the Computer Systems Laboratory.]

Table 15: OPTICAL-FIBER COMMUNICATIONS

Optical Fibers	$	Labs
silica	p	E
halide (long-wavelength)	-	E
Optoelectronic Components		
sources	f	E
detectors	f	E
waveguides	f	E
modulators	p	E
couplers	p	E
hybrid and integrated-optical circuits	-	E
materials characterization	-	E
amplifiers	-	E
multiplexing	-	E,O
switches	-	E
coherent communications	p	E,O
system performance measures	-	E

f = fully funded E = EEEL
p = partially funded O = Other Lab

Implementation examples. For silica fibers, new measurement capability will be developed for better control of geometric properties (e.g., diameter and ovality) in order to improve the mating of optical fibers at interconnections for reduced losses of signal strength. Also for fibers, a new measurement technique will be standardized for determining the degradation of pulse shape with distance down a fiber (chromatic dispersion), based on the results of an EEEL measurement intercomparison with industry. For sources, new convenient reference standards and measurement capability will be developed for determining the wavelength and strength of emitted light, and the noise (unwanted optical energy) in the emitted light. For couplers, new measurement techniques will be developed for determining the efficiency of transfer of energy from one light path to another. For integrated optics, EEEL will develop measurements for key circuit properties, such as coupling losses within the circuits and cross-talk between circuit elements. For related materials characterization, EEEL will develop measurement capability and reference materials data with focus first on magneto-optical and electro-optical properties, and then on thermo-optical and acousto-optical properties. This reference materials data is essential to industrial design of components and manufacturing processes and is especially critical for optical integrated circuits. As part of these many measurement-related efforts, some selective generic-technology development will be undertaken, supporting, in particular, new light sources required for measurement systems but useful for other applications as well.

VIDEO

Importance of Field

Video technology, to date, has not been able to exploit the ability of human vision to see both high resolution and smooth motion at the same time. Computers have focused on high resolution to permit clear display of text at the expense of smooth motion. Television has focused on smooth motion at the expense of clear display of text. Now advances in the several technologies that underlie video technology promise both capabilities together. As a result, the services of computers, televisions, and telecommunications systems can be merged to provide a powerful new video "window" to the information age. This merger will provide new capabilities for diverse applications, such as education, entertainment, medicine, defense, security, transportation, publishing, advertising, and banking. For example, advanced video technology will serve business and government broadly through improved office automation, electronic mail, and teleconferencing. If the prospect of on-demand services through networks can be added, users will gain access to libraries of text, audio, and video information whenever they wish. Exciting possibilities include on-line access to newspapers and related video archives, to major repositories such as the Library of Congress and the National Archives, and to the great lecturers at the universities of the world, among many others. A key aim for networked advanced video systems is the availability of such enormous information capacity at sufficiently low cost that the diverse information interests of the entire population, in smaller segments, can be better served, not just the majority or plurality interests.

While definitions of *advanced video* vary, the term generally suggests four to ten times the resolution of present-day television at one to two times present frame rates (pictures per second). This is an enormous amount of information. At ten times present-day resolution with the same frame rate, an advanced video signal would contain about 1 gigabit per second of information. This is approximately the entire information-carrying capacity of the best present optical-fiber communications lines.

The potential market for advanced video systems is difficult to project with confidence, but a large market is possible. A key part of this market is high-definition television (HDTV), including associated video cassette recorders. For the consumer portion of this market, the projections from several sources, while differing, suggest a U.S. market of order $10 billion per year (1988 dollars) by the year 2003.[19] The total world market for electronic products is typically two to three times the U.S. market alone, so the world consumer market may be in the range of $20-30 billion per year (1988 dollars) by the year 2003. Commercial and industrial markets of HDTV-related products, based on an estimate by the Japanese Ministry for Trade and Industry (MITI), may be two-thirds the size of the consumer market.[20] Thus a rough estimate of the total world market might be $33-50 billion per year (1988 dollars) by the year 2003. Other applications of advanced video would add to this market size. The market for the services of advanced video systems will be even larger.

Trends

Marketplace. The potential of advanced video systems to drive technical progress and markets for the supporting technologies is notable. Advanced video systems are already driving many aspects of display technology and will likely contribute significantly to the markets for dynamic random access memories (DRAMs), logic circuits, and other components. Further, advanced video systems may leverage the extension of fiber to the home.[21]

U.S. competitiveness in advanced video faces a major uphill battle. Japan is in the lead with the Europeans close behind. The U.S. hopes to set a broadcast standard for advanced video by the spring of 1993. Japan will be able to adapt to any standard that the U.S. adopts.[22] Japan already has a full line of advanced video products on the market that reflect its own standards.

More generally, the overall consumer-electronics picture reflects the seriousness of the competitive challenge. In 1990 the U.S. had $1.8 billion of exports and $13.1 billion of imports. Direct Japanese imports accounted for $4.6 billion, but a large fraction of the remaining imports, and of domestic production, was accomplished in Japanese-owned facilities in the U.S., Mexico, and the Pacific Rim countries. At the present time only one U.S-owned manufacturer of television sets has survived; that manufacturer has 13% of the U.S. market for color television sets. Further, the movement of foreign-owned facilities to the U.S. is abating, with Mexico providing a greater draw.[23]

Technical. Advanced video technology is one of the most demanding technologies any country has ever attempted to commercialize. Realization of practical advanced video systems requires achieving very high performance levels at acceptable costs from five supporting technologies.

> *High-resolution vision* systems must capture the signals used for advanced video systems. Video production requirements are likely to be ten times present levels, even if a lower resolution is selected for delivery to viewers. Vision systems are principally video cameras, but also include scanners that read documents, including photographs, and computers that synthesize images, including moving images. A key demand placed on new video cameras will be their ability to deliver adequate levels of resolution in the presence of moving images.
>
> *Real-time signal processing* will be necessary for most video systems to process information as fast as it is generated. This is necessary for live television and for playing back recorded material at natural speeds. Real-time signal processing is principally relevant to digitally encoded forms of advanced video technology which facilitate the manipulation of data. Digital signal processing can be used to edit video material, to create special effects, to reduce noise, and to compress and decompress information to reduce demands on the capacity of storage and transmission systems. The current trend favors digital formats.
>
> *High-data-rate transmission* will be necessary to carry advanced video signals. The highest speed cable technology is optical-fiber communications, and the highest speed radio technology is microwave transmission (e.g., satellites). Both have the capacity for *two-way transmission* and therefore for on-demand services, as well. To exploit them fully, a comprehensive international network strategy, such as the high-speed (broadband) Integrated Services Digital

Network (ISDN), will be needed. The U.S. and the international community are clearly behind ISDN; international standards for the high-speed version will be voted on for adoption by the International Consultative Committee for Telephone and Telegraph (CCITT) in 1992. This version will offer a capacity of 622 megabits per second for individual users, enough for many compressed advanced video signals. The movement toward an optical-fiber network of some form seems certain, although the timing is not.[24] For *one-way transmission*, with high compression and possibly reduced resolution levels, both terrestrial-broadcast and coaxial-cable technologies, which have lower information capacities, can also serve.

High-density information storage will be required to record and playback the images of advanced video systems in real time. Magnetic tape is attractive because it permits major increases in storage capacity by using longer tapes (to increase storage area). Magnetic disks and optical disks do not lend themselves as easily to large increases in area. At present there is no real alternative to magnetic tape, but there is long-range interest in three-dimensional laser-driven optical storage and in semiconductor memory of extraordinary density, both of which could eliminate mechanical movement and thus improve the speed of response.

High-resolution displays may take several forms. Cathode-ray tubes can already be made with the performance required for advanced video technology; but they are very large, heavy, and expensive. Flat-panel displays are on the rise, but require much additional development. The first full-color flat-panel displays, made from liquid crystals, are available in the market and show some promise. Challenges include achieving adequate brightness levels, proper color rendering, and low cost. Other approaches, such as flat versions of cathode-ray displays based on semiconductor technology, are being investigated.

Strategic Directions

Strategy. Because of the broad scope of technical advances that are necessary to commercialize advanced video, the required infrastructure support will be significant. EEEL is developing a plan for response. The first elements of that plan are in place in the areas of real-time signal processing and high-speed transmission and will be described here; other elements will be defined during the coming year until all five of the supporting technologies in Table 16 have been addressed. To support needed work, NIST and DARPA are establishing at NIST a *digital information processing facility* with a dedicated massively parallel computer designed for video work.

Table 16: VIDEO

	$	Labs
High-Resolution Vision		
(to be defined)	-	-
Real-Time Signal Processing		
algorithm evaluation		
compression	p	E,O
High-Speed Transmission		
network-interfacing evaluation		
parallel processors	-	O
video components	-	E,O
High-Density Information Storage		
(to be defined)	-	-
High-Resolution Displays		
(to be defined)	-	-

f = fully funded E = EEEL
p = partially funded O = Other Lab

For real-time signal processing, NIST will focus on the development of methods for evaluating compression algorithms. The performance of compression algorithms is critical in determining the required capacities of transmission and storage systems, and therefore is a major determinant of system cost. For high-speed transmission, NIST will develop figures of merit, measurement methods, and standards information for the interface of video components and parallel processors with networks. Special challenges are anticipated because of the high rate of data transfer. NIST anticipates a comprehensive program for support of displays in the future. NIST will address measurement support for high-density information storage as part of a separate effort in the magnetics field because of that work's applicability beyond video; any special problems that surface related to video will be addressed later as part of the video field. Similarly, measurement needs for high-speed transmission technologies generally will be addressed as part of the microwave and optical-fiber communications fields. These assignments of projects to the various fields of electronics follow the prescription accompanying Table 2.

Implementation Examples. For compression-algorithm evaluation, both reversible compression techniques (no loss of information after expansion) and irreversible compressions techniques (some loss of information) will be supported, as will both progressive scanning (successive lines) and interlaced scanning (alternate lines). For network-interface evaluation, planned work will address both massively parallel computers, which will be needed for real-time signal processing at the high resolutions of advanced video, and key video components such as sources (cameras, scene simulators, encoders), receivers (displays, decoders), and storage devices (which may act as either sources or receivers).

Table 17: FACILITIES CONCERNS

Environmental Control
particulates
humidity
temperature
vibration
acoustical noise
electromagnetic fields
Services
power quality
digital networking

VII. FACILITIES

General Facilities Concerns

EEEL plans to address a number of general concerns as it moves to improve its facilities. Those concerns are outlined in Table 17. They fall into two categories: environmental control and services. Under the category of *services*, "digital networking" refers to the need for improved communication both with outside laboratories and among instruments within different NIST laboratories.

Major Facilities Plans

EEEL's strategic plan for improving its facilities is summarized in Table 18. The table addresses only major facilities, which are those valued at $1 million or more. The table indicates if EEEL presently has a facility of that size for a given field, and notes the status pursued for both 1995 and 2001. A facility *upgrade*, as used here, means a major addition of capability, not just a routine replacement of equipment. A *new* facility, as used here, is one entirely new or one so different from its predecessor that it requires a new location. EEEL's ability to pursue these plans depends on the success of associated budget initiatives since no major facilities funding is available independent of initiatives.

Table 18: MAJOR FACILITIES PLANS

Fields	Present	1995	2001
semiconductors	yes	upgrade	new
superconductors	yes	same	new
magnetics	-	new	new
microwaves	yes	same	new
lightwaves			
lasers	yes	new	new
optical-fiber communications	yes	upgrade	new
optical information storage	-	*	*
optical processing/computing	-	*	*
optical-fiber sensors	-	-	-
power networks	yes	same	new
video	yes	upgrade	upgrade
Cross-Cutting Fields			
electromagnetic compatibility	yes	new	same
complex-system description	-	*	*
complex-system testing			
high efficiency	-	*	*
high accuracy	yes	upgrade	new

* = under study

Here are some highlights of the plan. By 2001, EEEL proposes to establish, jointly with other NIST Laboratories, major facilities for microfabrication and micromanipulation at both the Gaithersburg and the Boulder sites. The new facilities would support collaborative programs for measurement development for integrated circuits and microdimensional electromagnetic measurements generally for the fields of semiconductors, superconductors, magnetics, microwaves, and lightwaves. EEEL also proposes to establish facilities for measurement development for microwave antennas and electromagnetic compatibility. Included would be chambers and ranges suitable to accommodate emerging high-performance, high-frequency microwave antennas. The facilities would also support measurement development needed to assure compatible operation of increasing numbers of electronic products. By 2001, EEEL also proposes new electromagnetically quiet laboratories for work on the most fundamental electrical quantities at the highest possible absolute accuracies. EEEL would also build a new high-voltage laboratory to support high-performance components for power networks.

VIII. 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 publication requests that themselves number several thousand per year. Given this definition, EEEL served about 2150 different customer organizations during the past five-year period. Table 19 shows how those customer organizations break down by the percentage of the number of organizations of each type. 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.

Table 19: 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%
(rounding error)	101%

EEEL's customers include 102 of the Fortune 500 companies and 44 of the top 100. Table 20 shows the percentage of companies, from each of several key categories of Fortune 500 companies, which are EEEL's customers. Among all companies, within and outside the Fortune 500, EEEL numbers as customers almost all of the major aerospace companies, more than half of the major electronic and communications equipment manufacturers, all three major automobile manufacturers, and a very large number of companies (42) in pharmaceutical, medical, and health areas, among many others.

Table 20: 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 U.S. 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 21 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 is 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. EEEL serves the broad spectrum of its customers with a wide variety of deliverables; those deliverables were summarized in Table 5. EEEL will renew its efforts to alert potential customers of EEEL services during this year.

Table 21: 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. [The high economic leverage of this calibration service is described in section IX under "Watthour Meter Calibration Project".] 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.

Future Directions

EEEL sees a number of forces, or trends, many interrelated, that will likely influence its customer base. Some of these forces will increase the size of the customer base and the intensity of EEEL's interactions. Other forces will affect the dominant types of services requested or the motivation for requesting them. Representative forces are shown in Table 22. Electronic technology is advancing rapidly, giving rise to measurement problems of increasing difficulty. Growing concern for U.S. competitiveness is increasing the demand for measurement support needed for recovery. The merging of the electronic technologies will increase the number of customers which need measurement assistance in multiple electronic technologies. The discovery of the effectiveness of collaboration, among companies and between Government and industry, is increasing the demand for measurements supportive of collaborative activities, including effective technology transfer. The internationalization of markets and the emergence of economic blocks (European Economic Community) will increase the number of customers concerned with international standards issues; more generally, increasing requirements for standards compliance are moving beyond the reach of many small companies. Growth in capital-intensive manufacturing, necessary for rapid commercialization on an economically significant scale, will favor large companies.

Table 22: FORCES SHAPING CUSTOMER BASE

advances in technology
growing concern for U.S. competitiveness
merging of electronic technologies
discovery of effectiveness of collaboration
growth in capital-intensive manufacturing
internationalization of markets

IX. IMPACT

EEEL sees its impact daily in convincing forms: high activity associated with delivery of its findings (summarized in Table 5); speed of industrial adoption of findings; clamor for more assistance; reports of impact from industry; and continued funding from other agencies. EEEL develops further impact information by conducting a variety of studies with differing traits as outlined in Table 23. The *analytical* studies provide benefit:cost ratios, social rates of return, and other indicators of economic impact.[25] These studies are the most difficult and expensive to conduct because measurement technology is *implicit* in nearly *every aspect* of industry's performance; thus identifying and isolating all of the effects are difficult. Ironically, this is the same reason for the high impact of measurement technology. Overall, the analytical impact studies for individual projects have shown benefit:cost ratios from 5:1 to over 100:1 and social rates of return with a median above 140 percent. This median is higher than that for industrial innovations generally, cited variously as 56 percent (Edwin Mansfield) and 99 percent (J.G. Tewksbury).[26] This median also falls in the top half of the range cited by the President's Science Advisor as applicable to all basic and applied research and development: 20 to 200 percent.[27] Key examples of impact are provided below. They are drawn from different fields of electronics. They are representative of the different types of impact studies that EEEL conducts. EEEL is presently conducting additional impact studies as noted in Table 7.

Table 23: IMPACT STUDY TRAITS

Scope	single project
	entire program
Chronology	retrospective
	prospective
Formality	anecdotal
	analytical

Semiconductors

Entire Program and Selected Projects (retrospective, analytical). The impact of the semiconductor program was analyzed in 1981 by the Charles River Associates (CRA) under contract to NIST. CRA employed a *production function* approach to study the program's impact on the revenue growth and productivity of the semiconductor industry for a sample of 26 semiconductor manufacturers. They found that "by acquiring significant amounts of technical information from NBS [NIST], a firm could increase the productiveness of its own R&D activity by at least one third." The study also estimated that "during the period 1973 to 1977 the cumulative effect of technical information acquired from NBS was to increase the overall industry productivity level by approximately 1 percent." These productivity benefits were "in the range of $30 to $50 million per year over this period." As determined by a separate analysis, the increase of 1 percentage point was about 4 percent of the entire productivity increase of the semiconductor industry over the same period.[28] In addition, CRA conducted *case studies* of three NBS projects believed to be of high impact: silicon resistivity, wire bonding, and thermal properties. These three projects represented 40 percent of all NBS semiconductor-program expenditures during the period of peak work on them and yielded a median benefit:cost ratio of 12:1 and a median social rate of return of 140 percent.[29]

Microwaves

Near-Field Scanning Measurements of Antennas Project (retrospective, anecdotal). Based on theory developed originally for determining the speed of light, EEEL has developed techniques for determining the radiation pattern, far from antennas, by measurements made close to the antennas, reducing the real estate required for the measurements from miles of outdoor land to a single large room. The new measurement approach is also faster and more accurate, and it provides more detail; it is useful in production as well as in development. The near-field scanning method has been adopted by 30 U.S. companies and many government agencies which now have a combined total of

54 near-field facilities, resulting in great impact. RCA has stated that it saved over $6 million in the costs of building and testing Aegis radar antennas of the type installed on U.S. Navy cruisers. Hughes found that the time needed to measure complex phased-array antennas for the U.S. Army was reduced from 1 month to 12 hours. TRW estimates that it is saving $35 million in testing costs from the application of near-field scanning in four facilities.

Lightwaves: Optical-Fiber Communications

Optical-Fibers Project (retrospective, analytical). Economist Albert N. Link has prepared a report (1990) under contract to NIST, assessing the economic impact of 22 voluntary industry standards for determining the critical properties of optical fibers; EEEL provided the measurement basis for these standards. Link calculates that the cost savings realized by producers and users of optical fibers in executing market transactions are in the range $8 to $11 million per year. Link also estimates that the benefit:cost ratio associated with this project falls between 16 and 22 and that the social rate of return is 173 percent. Further, Link noted that one participating fiber manufacturer reported a *factor* of 25 increase in sales attributable to the NIST-supported standards.[30]

Optical-Fiber Communications Program (prospective, analytical). A detailed report (1985) was prepared by Gregory Tassey, senior economist at NIST, on the prospective economic impact of NIST measurement-research support for the emerging optoelectronics industry, with emphasis on optical-fiber communications. He concluded that for a full measurement-research program (similar to the one in Table 15) "a reasonable projection of the aggregate annual cost savings to the optoelectronics industry from NBS [NIST] research is $100 to $200 million" *for productivity growth alone*.[31]

Power Networks

Watthour Meter Calibration Project (retrospective, anecdotal). The electric power industry includes over 3200 utility companies who sell about $169 billion worth of electricity annually (1989). All of this electricity is metered through watthour meters, and virtually all of these are calibrated against NIST standards. NIST performs about 130 power and energy calibrations annually on reference standard watthour meters. The manufacturers of watthour meters use these reference standards to calibrate about 9 million watthour meters per year. NIST power and energy calibrations also support suppliers who sell more than $9 billion per year of transformers and switchgear for power networks.

Electromagnetic Compatibility

The Crawford Cell Project (retrospective and prospective, anecdotal). EEEL pioneered and popularized the use of a special enclosed electromagnetic chamber for testing the susceptibility of electronic equipment to electromagnetic interference (EMI). The cell was named the Crawford cell by industry after an NIST engineer. The cell has become a critical tool for testing for potentially serious EMI-induced malfunctions (helicopter crashes, electronic-brake failures in vehicles, etc.). With EEEL assistance, the military is now designing a $15-million facility to test entire vehicles, such as tanks and airplanes, for susceptibility to electromagnetic radiation, in fractions of the time required by other methods. The "big three" of the automotive industry are now constructing Crawford cells for testing automotive components. Very soon, all of the automotive industry's annual production of $141 billion per year of vehicles (1991)[32] may be based on designs tested in the Crawford cell. Both the private sector and the Government now recognize that great savings can be realized by testing *before* production as part of total-quality management. To support the growing demand for the cells, more than a dozen U.S. and foreign companies are now marketing them.

ENDNOTES

1. *1991 Electronic Market Data Book*, Electronic Industries Association, pp. 4, 113 (1991).

2. The 51 collaborative efforts in place as of the end of FY 1990 were distributed 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 involve the transfer of funds.

3. A full analysis, entitled "Role of Measurements in Competitiveness", will appear as a chapter in *Measurements for Competitiveness in Electronics*, Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, to be published during 1991.

4. A U.S. organization of government and industry called IGES/PDES (Initial Graphics Exchange Specification/Product Data Exchange using STEP) is developing standards for computer-based descriptions of electronic (and other) systems. When those standards are adopted internationally, each will become a Standard for Exchange of Product Model Data (STEP).

5. *Toward a National Semiconductor Strategy*, Second Annual Report of the National Advisory Committee on Semiconductors, Volume 1, pp. 18-26 (February, 1991). The National Advisory Committee on Semiconductors was created by the Congress (Public Law 100-418) in 1988 and includes the Secretaries of Defense, Commerce, and Energy; the Director of the Office of Science and Technology Policy; and the Director of the National Science Foundation; plus eight members appointed by the President and drawn from the semiconductor industry and the fields of technology, defense, and economic development.

6. The Council is a "nonprofit, nonpartisan organization of chief executives from business, higher education and organized labor who have joined together to pursue a single overriding goal: to improve the ability of American companies and workers to compete more effectively in world markets." *Gaining New Ground: Technology Priorities for America's Future*, Council on Competitiveness, pp. 6-11 and 73 (1991).

7. *Emerging Technologies in Electronics and Their Measurement Needs*, Second Edition, Center for Electronics and Electrical Engineering [now Electronics and Electrical Engineering Laboratory], National Institute of Standards and Technology, pp. 11-30, 55-62, 113-138, and 139-162 (February, 1990).

8. *The VLSI Manufacturing Outlook*, VLSI Research, Section 1.9.1, p. 1 and Section 1.9.3, pp. 1, 5 (1990).

9. *The VLSI Manufacturing Outlook*, VLSI Research, Section 1.9.3, pp. 1, 5 (1990).

10. *The VLSI Manufacturing Outlook*, VLSI Research, Section 1.9.1, p. 1 (1990).

11. Market data on silicon materials obtained by Dataquest from Rose Associates.

12. *Emerging Technologies in Electronics and Their Measurement Needs*, Second Edition, Center for Electronics and Electrical Engineering (now Electronics and Electrical Engineering Laboratory), National Institute of Standards and Technology, pp. 118-122. To obtain an estimate of U.S. shipments for 1989 (in constant 1988 dollars), the value for 1988 was increased by the real percentage rate of growth from 1988 to 1989 for all "Radio Communication and Detection Equipment", as cited in the *1991 U.S. Industrial Outlook*, International Trade Administration, U.S. Department of Commerce, p. 31-1 (January, 1991). Since most microwave equipment is included in this category, this percentage represents the best available estimator for microwave equipment.

13. Based on the pattern for the parent category of "Radio Communications and Detection Equipment" (SIC 3663, 3669, and 3812) which contains most microwave equipment, *1991 U.S. Industrial Outlook*, International Trade Administration, U.S. Department of Commerce, p. 31-1 (January, 1991).

14. Based on the SIC categories grouped to form "Radio Communication and Detection Equipment" which is dominated by microwave equipment. *1991 U.S. Industrial Outlook*, International Trade Administration, U.S. Department of Commerce, p. 31-2 (January, 1991).

15. *1991 U.S. Industrial Outlook*, International Trade Administration, U.S. Department of Commerce, pp. 31-5 (January, 1991).

16. *1991 U.S. Industrial Outlook*, International Trade Administration, U.S. Department of Commerce, p. 31-12 (January, 1991).

17. *International Competitiveness Study of the Fiber Optics Industry*, International Trade Administration, U.S. Department of Commerce, p. 25 (September, 1988).

18. *1991 U.S. Industrial Outlook*, International Trade Administration, U.S. Department of Commerce, p. 31-13 (January, 1991).

19. *The Big Picture: HDTV & High-Resolution Systems*, Office of Technology Assessment, Congress of the United States, p. 84 (June, 1990). Reflects projections from the Electronic Industries Association, the American Electronics Association, and the National Telecommunications and Information Administration of the U.S. Department of Commerce.

20. *The Big Picture: HDTV & High-Resolution Systems*, Office of Technology Assessment, Congress of the United States, p. 84 (June, 1990).

21. *The Big Picture: HDTV & High-Resolution Systems*, Office of Technology Assessment, Congress of the United States, p. 86-88 (June, 1990).

22. *1991 U.S. Industrial Outlook*, International Trade Administration, U.S. Department of Commerce, pp. 38-12 and 38-14 (January, 1991).

23. *1991 U.S. Industrial Outlook*, International Trade Administration, U.S. Department of Commerce, pp. 38-12 and 38-14 (January, 1991).

24. *The Big Picture: HDTV & High-Resolution Systems*, Office of Technology Assessment, Congress of the United States, p. 84 (June, 1990).

25. 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 resulting benefits (during use of project results). The technique considers the time value of money and the return that might have been obtained from alternative-opportunity investments. The social rate of return is 0 percent if the benefits returned to society are equal to costs of the project, after the adjustments mentioned. The social rate of return rises as the benefits rise relative to the costs. It is very much like an annualized return on investment with the cost of the foregone alternative opportunity reflected. For example, if one invests money in the stock market, the success of that investment decision is best reflected by the increase made over the return from a readily available alternative, such as placing the same amount of money in a savings account.

26. Economists Edwin Mansfield and J.G. Tewksbury have estimated the median social rate of return to industrial innovations at values of 56 percent and 99 percent, respectively, as reported by Charles River Associates Incorporated, *Productivity Impacts of R&D Laboratories: The National Bureau of Standards' Semiconductor Technology Program*, pp. 90 and 93 (May, 1981).

27. 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).

28. G. C. Tassey, R. I. Scace, and J. C. French, "Economic Impact of Standards on Productivity in the Semiconductor Industry", *Semiconductor Fabrication: Technology and Metrology, ASTM STP 990*, Dinesh C. Gupta, editor, American Society for Testing and Materials, pp. 450-459 (1989).

29. *Productivity Impacts of NBS R&D: A Case Study of the Semiconductor Technology Program: Summary Volume*, Charles River Associates, pp. 3, 19, 20, and 41 (June, 1981).

30. Albert N. Link, *Economic Impacts of NIST-Supported Standards for the U.S. Optical Fiber Industry: 1981-Present* (draft, September, 1990).

31. Gregory Tassey, *Planning Report 23: Technology and Economic Assessment of Optoelectronics*, National Bureau of Standards [now National Institute of Standards and Technology], p. 63 (October, 1985).

32. *1991 U.S. Industrial Outlook*, International Trade Administration, U.S. Department of Commerce, p. 37-2 (January, 1991).

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10. SUPPLEMENTARY NOTES

11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

Among U.S. manufacturing industries, the electronics industry is the largest employer (1.94 million) and is a close second in shipments ($266 billion) to the chemical industry (1990). U.S. competitiveness in many fields of electronics has been declining. Improved competitiveness will require outstanding performance from manufacturers in every step required to put a product into service to a buyer: research and development, manufacturing, marketplace exchange, and after-sales support. All of these steps are highly measurement intensive and have outstripped available measurement support. Improved measurement support is an essential part of any successful strategy for improving U.S. competitiveness.

The Electronics and Electrical Engineering Laboratory (EEEL), within the National Institute of Standards and Technology, as part of a continuing study of the electronics industry, is identifying measurement needs in important fields of electronics. semiconductors, superconductors, magnetics, microwaves, lightwaves (optoelectronics), power networks, video, electromagnetic compatibility, and complex-system description and testing. This document describes EEEL's strategic plan for a response in terms of both general strategic directions across all of these fields and specific strategic directions for four fields: semiconductors, microwaves, optical-fiber communications, and video. The plan relates these directions to important goals for improved U.S. competitiveness.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

competitiveness; electrical engineering; electrical power; electronics; electronics industry; measurements; microwaves; optical-fiber communications; semiconductors; video

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