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Electronics and Electrical Engineering Laboratory

STRATEGIC PLAN For Fiscal Years 1999-2004

Electronics and Electrical Engineering Laboratory

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

January 1999

NIST

EEEL SEEKS YOUR COMMENTS

NIST's Electronics and Electrical Engineering Laboratory (EEEL) reviews its plans regularly to keep them focused on the most important needs of the U.S. electronics, electric-power, and electrical-equipment industries. Comments on this plan are invited and should be sent to the following address:

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Bibliographic Information

Abstract

The Electronics and Electrical Engineering Laboratory (EEEL) promotes U.S. economic growth by providing measurement capability of high impact focused primarily on the critical needs of the U.S. electronics and electrical industries, and their customers and suppliers. This measurement capability promotes economic growth by improving the *competitiveness* of U.S. industries. This capability is part of the national infrastructure that helps attract and retain businesses and jobs in the United States. EEEL focuses on measurement capability that U.S. industries need but cannot provide for themselves, for technical, economic, or other reasons. The beneficiaries include U.S. industry, government, academic, other organizations, and the general public.

The supported electronics and electrical industries are highly important to the U.S. economy. In round numbers, the electronics industry ships $400 billion of products each year. The electrical-equipment industry ships $100 billion of products each year. Together these two industries represent 12 percent of the annual shipments of all manufacturing industries. The electric-power industry, a service industry, relies on the electrical-equipment industry for power equipment and uses that equipment to provide $200 billion of electricity each year. These three industries are enabling industries for the entire U.S. economy. Virtually all other manufacturing and service industries rely on these three industries for equipment, power, information and control technology, and related services.

EEEL's measurement capability is an important part of the *tools* that manufacturers need to conduct research and development toward new products, to manufacture those products, to market them successfully, and to support them after sale. Successful marketplace exchange requires proving product performance to customers, and proving compliance with domestic and international requirements that would otherwise bar market entry. EEEL's measurement capability is also important to the success of materials, information services, and energy providers. Examples include the telecommunications and electric-power providers, as they seek to remain competitive while addressing new technical challenges inherent in deregulation.

EEEL's strategic plan describes important measurement contributions to the supported industries and the nation. The projects selected result from close interaction with industry and government to identify the needs most important to economic growth and competitiveness.

Keywords

communications, competitiveness, computers, digital electronics, displays, economic growth, electrical equipment, electrical power, electrical quantities, electronic data exchange, electronics, integrated circuits, magnetics, measurement instrumentation, measurement reference standards, measurements, microwaves, optical-fiber communications, optoelectronics, radio frequency, semiconductors, sensors, superconductors, telecommunications, video

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PREFACE

This Strategic Plan supports effective management of the Electronics and Electrical Engineering Laboratory (EEEL). This laboratory is one of eight laboratories that comprise the Measurement and Standards Laboratories at the National Institute of Standards and Technology (NIST). NIST itself is an agency within the U.S. Department of Commerce.

The format chosen for the Strategic Plan is responsive to the Government Performance and Results Act of 1993 (GPRA). (Terms with specially defined meanings in the GPRA, like Strategic Plan, have been capitalized here.) This Strategic Plan also specifies Performance Goals for multiple years. As a result, this document supports the development of both the Strategic Plan and the Annual Performance Plans required of the Department of Commerce by the GPRA. The scope of EEEL's Performance Goals is considerable, so only a selection from the most important can appear here. For a complete accounting, see EEEL's *1999 Program Plan* (228 pages), January 1999.

The format of this plan was derived from *OMB Circular No. A-11, Part 2: Preparation and Submission of Strategic Plans and Annual Performance Plans*. The table below shows how the sections in the OMB circular relate to the sections of this plan. Elements (2) and (4) are addressed in a single section of this plan called "Goals and Objectives". This approach relates Objectives to Performance Goals by stating each Performance Goal immediately after the Objective supported. The other four elements track one-to-one with the sections of this plan.

Circular Section Content	Circular Section Number	EEEL Strategic Plan
(1) Mission Statement	210.6	Mission Statement
(2) Goals and Objectives	210.7	Goals and Objectives
(3) how they will be achieved	210.8	Strategies
(4) relationship to Performance Goals in Annual Performance Plan	210.9	(Goals and Objectives)
(5) key factors affecting achievement	210.10	Factors Affecting Achievement
(6) program evaluations used, and scheduled	210.11	Program Evaluations

The Goals expressed in this plan are generally within EEEL's span of influence. The Objectives are generally within EEEL's span of control, as defined in the OMB Circular. Exceptions are noted where they occur.

This plan has been written to address Evaluation Factors 1 through 6 of the document "Interim Evaluation of Draft Strategic Plans". The Evaluation Factors track with elements (1) through (6) above, respectively. Evaluation Factors 7 through 10 are addressed in plans at higher organizational levels. This approach simplifies the use of this document by the Department of Commerce in responding to the GPRA.

NSP 1
NSP 1.2
NSP 1.2.3

This plan supports the NIST *Strategic Plan* but has been written to be freestanding. The connection to the NIST *Strategic Plan* is made through entries in the left margin. In the example to the left, NSP 1 would refer to Goal 1 in the NIST *Strategic Plan*. NSP 1.2 would refer to Objective 2 under Goal 1. And NSP 1.2.3 would refer to Strategy 3 under Objective 2 under Goal 1.

In EEEL's other planning documents, EEEL's work is divided into *programs* that provide a structure for description. To track to these programs, each Objective in this plan ends with a three-letter code in brackets, such as [SEM] for "Semiconductors". This code identifies the EEEL program conducting the work. The program names are listed alphabetically below, along with the associated codes:

Electromagnetic Compatibility	EMC
Electronic Data Exchange	EDE
Low Frequency	LFQ
Magnetics	MAG
National Electrical Standards	NES
Optoelectronics	OPT
Power	PWR
Radio Frequency	RFQ
Semiconductors	SEM
Superconductors	SUP
Video	VID

The scope of this plan includes all work managed by EEEL, whether conducted within EEEL or in other parts of NIST, and whether funded by (1) direct appropriations to NIST, (2) other agencies, or (3) other sources outside NIST. The above programs are conducted primarily within EEEL, drawing on skills from the other NIST laboratories, as needed. In addition, EEEL manages two programs that are conducted NIST wide. These programs are shown below, along with their associated codes:

Law Enforcement Standards	LES
National Semiconductor Metrology Program	NSM

Performing organizations that conduct work for these two programs, and that are outside EEEL, are referenced after each applicable Objective in this Strategic Plan.

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The following individuals contributed to the content of this strategic plan or to the guidance used in its preparation. All EEEL staff contribute to the implementation of this plan.

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MISSION STATEMENT

The Electronics and Electrical Engineering Laboratory (EEEL) promotes U.S. economic growth by providing measurement capability of high impact focused primarily on the critical needs of the U.S. electronics and electrical industries, and their customers and suppliers.

U.S. economic growth requires international competitiveness, which requires new technology, which requires new measurement capability, which must be based on world-class scientific research. Therefore, EEEL pursues world-class capability in measurements to facilitate U.S. economic growth. This capability is part of the national infrastructure that helps attract and retain businesses and jobs in the United States. This capability is an *essential tool* that industry uses to develop and market new products. EEEL focuses on measurement capability that U.S. industries need but cannot provide for themselves for technical, economic, or other reasons. The needed capability reflects the rapidly changing nature of electronic and electrical technologies that are both global and critical.

Provide Measurement Capability that U.S. Industries Cannot Provide

NIST provides only that measurement capability that U.S. industries cannot provide for themselves. There are several circumstances under which NIST's assistance to industry is appropriate: (1) Special measurement expertise is required (often multidisciplinary) that is not available in industry; (2) industry cannot recover the costs of measurement development that is so fundamental and so broadly beneficial; (3) NIST's acknowledged impartiality and measurement competence are required to gain acceptance among manufacturers, suppliers, and customers in order to realize maximum benefits to the nation; or (4) NIST's imprimatur as the lead U.S. agency for measurements is required to gain international acceptance so that U.S. products can be sold abroad.

Table 1: Manufacturers' Challenges

Research and Development
Manufacturing
Marketplace Exchange
After-Sales Support

Table 2: Product Characteristics for Competitiveness

Performance
Quality and Reliability
Compatibility
Safety

Focus on Improving Competitiveness

EEEL strengthens the U.S. economy by strengthening the international competitiveness of U.S. manufacturers. To be competitive, a manufacturer must meet the challenges in Table 1. Success in addressing the first two challenges is largely dependent on a manufacturer's ability to realize desirable product characteristics, especially those in Table 2. Success in addressing all four challenges in Table 1 requires meeting a number of marketing requirements, especially those in Table 3. EEEL helps manufacturers address all of the challenges in Tables 1, 2, and 3. This plan shows how EEEL's contributions impact the factors in these tables and thus improve competitiveness.

Table 3: Marketing Requirements for Competitiveness

Access to market
Agreement with customer on product characteristics
Attractive price
Timely delivery
Good after-sales support

Address Economically Significant Industries

EEEL assures the high impact by addressing three economically significant industries. The estimated shipments of these industries for 1998 are shown in Table 4 to the nearest $100 billion. The shipments of the electronics and

Table 4: Shipments of Customer Industries (1998 estimates)

Industry	Shipments ($billions)
Electronics	400
Electric Power	200
Electrical Equipment	100
	700

electrical-equipment industries together represent approximately 12 percent of the shipments of all U.S. manufacturing industries.

Among U.S. manufacturing industries, the electronics industry is the largest in shipments, followed by the automotive and chemical industries. The electronics industry is also the largest in employment, by a factor of two, with 1.7 millon employees.

The electric-power industry is composed of the providers of electricity, whether independent or owned by investors, government, or cooperatives. The $200 billion shown in Table 4 is the electricity they sell in a year.

The electrical-equipment industry makes equipment that provides electricity, through products such as generators, transformers, and batteries. This industry also makes equipment that converts electricity into other useful forms, through products such as motors, lighting, and heating elements.

The industries in Table 4 are enabling industries. All other industries, government agencies, and the public rely on these industries for power, equipment, information and control technology, and related services.

Further International Agreement on Measurements

EEEL also impacts U.S. strength in international trade by furthering international agreement on measurements. A key means of furthering agreement is comparing EEEL's measurements with those of counterpart measurement laboratories in other nations. Such agreement is necessary to meet the requirements for U.S. competitiveness embodied in Table 3, especially the first two: (1) International agreement enables U.S. manufacturers to *gain access to foreign markets* by proving compliance with the growing number of international written standards that might otherwise bar product entry. (2) International agreement enables U.S. manufacturers to *reach agreement with their own suppliers and customers*, both domestic and international, on product characteristics, so that sales can be completed.

NSP 1.1

Focus on Highest Impact Needs for Measurement Capability

EEEL determines the highest impact measurement needs requiring EEEL's assistance through workshops, surveys, studies, and visits to companies. For example, as shown in Table 5, EEEL has developed and published measurement-needs assessments for two of the three industries through which EEEL stimulates economic growth: the electronics industry and the electric-power industry.

EEEL's ability to anticipate industry's measurement needs benefits greatly from roadmaps developed by industry, including those in Table 6. The roadmaps lay out industry's plans for remaining competitive in future years. This information helps EEEL to understand how industry expects to evolve, and, therefore, what measurement capability industry will need, and when.

Table 5: Measurement Assessments Published

Measurements for Competitiveness in Electronics
Measurement Support for the U.S. Electric-Power Industry in the Era of Deregulation

Table 6: Industry Roadmaps and Sponsors

National Technology Roadmap for Semiconductors Semiconductor Industry Association
Optoelectronic Technology Roadmap Optoelectronics Industry Development Association (OIDA)
National Electronics Manufacturing Technology Roadmaps National Electronics Manufacturing Initiative
Storage Technology, Head Metrology Roadmaps National Storage Industry Consortium
Optical Disk Storage Roadmap National Storage Industry Consortium and OIDA
Electric-Power Roadmap

EEEL assists industry in roadmap development by determining the measurement implications for industry's planned route to remain competitive.

Assure Measurement Accuracy, Accessibility, and Applicability

EEEL pursues three important aims when developing measurement capability needed by the U.S. economy. These aims are shown in Table 7 and are highlighted throughout this plan. First, EEEL pursues ***measurement accuracy***. Above all, the United States relies on EEEL to provide the foundation for the measurement of all electrical quantities at the highest levels of accuracy. Second, EEEL pursues ***measurement accessibility***; that is, EEEL translates its measurement capability into forms that are technically and economically accessible to producers and consumers. Without such translation, that capability could not be readily adopted or afforded. Finally, EEEL pursues ***measurement applicability***, which is the translation of EEEL's measurement capability into forms applicable to specific problems. For example, a measurement method for voltage applicable at 0.000001 volts to support the semiconductor industry would not be applicable at 100,000 volts to support the electric-power industry, even though both measurements rely on the same measurement foundation within EEEL.

Table 7: Aims for EEEL's Measurement Capability

Accuracy
Accessibility
Applicability

GOALS AND OBJECTIVES (and responsive Performance Goals)

NSP 1.1
NSP 1.2

Goal 1: Strengthen Foundation for All Electrical Measurements

The foundation for all measurements is based on Measurement Reference Standards. They are electronic systems, special devices, or special materials that NIST develops. Each Measurement Reference Standard provides a high level of accuracy for a measured quantity fundamental to the measurement foundation. The expertise of many NIST laboratories is necessary to provide all of the Measurement Reference Standards needed for the measurement foundation.

NIST must transfer accuracy from these Measurement Reference Standards to millions of customers in industry, government, universities, and other organizations. To do this efficiently, NIST employs several approaches, but one is especially important for electrical quantities. NIST uses the Measurement Reference Standards to determine the accuracy of a relatively small number of high-performance measurement instruments provided by customer organizations. The instruments so evaluated are said to be "calibrated". They are then used by customer organizations to calibrate other instruments, for themselves and others, and so on in an ever expanding chain of calibrations. In this way, NIST delivers accuracy to millions of users through commercial channels and instrumentation.

NIST's Measurement Reference Standards must have high enough accuracy to support the most demanding users, and to provide a cushion for innovation. High *accuracy* is best achieved by basing the Measurement Reference Standards on the fundamental physics of nature. Such a basis is believed to be unchanging. Such a basis also furthers *accessibility* by enabling others to build Measurement Reference Standards of comparable accuracy; the fundamental physics of nature is accessible to all.

Table 8: Measurement Foundation for Electrical Quantities

Base Quantities
- time
- length
- ✓ **mass**

Electrical Quantities
- dc voltage
- dc current
- ✓ **ac voltage**
- ✓ **ac current**
- power
- impedance
  - ✓ **capacitance**
  - inductance
  - resistance

The quantities most important to the foundation for electrical measurements are shown in Table 8. The first three quantities—time, length and mass—are called *base* quantities. They are especially important because measurements of all electrical quantities, as well as many other quantities, are based on them. The quantities checked (✓) in the table are in particular need of improvement in either accuracy or accessibility. Each is discussed below. Then the route from the measurement foundation to competitiveness is discussed.

Mass

Time and length have an advantage compared to mass. The Measurement Reference Standards for time and length are based on the fundamental physics of nature, so they are very accurate and accessible. For example, time is based on counting a specified number of cycles of radiation emitted by a cesium atom under special conditions. The cesium atom is accessible to everyone. The Measurement Reference Standard for time is maintained by NIST's Physics Laboratory. Time can be measured more accurately than any other quantity.

Unfortunately, the Measurement Reference Standard for mass is not yet based on the fundamental physics of nature. Instead, mass is referenced to a single World Measurement Reference Standard, in the form of a cylinder of platinum-iridium alloy kept at the International Bureau of Weights and Measures (BIPM) in France. A copy is kept at NIST to serve as the U.S. Measurement Reference Standard, and its accuracy is established by comparison with the BIPM one. These cylinders are subject to change caused by factors such as the release of dissolved gases, or the loss of material during handling. This weak member in the measurement foundation limits the accuracy of measurements of mass, weight, electrical quantities, and other quantities, too. The first step to improving the accuracy of mass measurements is to determine how much the Measurement Reference Standard for mass is changing in time. Objective 2.1 below addresses this need. It may later lead to an electronic method for creating a new Measurement Reference Standard for mass that depends only on the fundamental physics of nature and that is, therefore, much more accessible.

> ***Objective 1.1***: Establish long-term accuracy of the electronic system, successfully developed in FY 1998, for monitoring the drift in the kilogram, based on the fundamental physics of nature. *Performance Goal: Achieve long-term uncertainty of one part in 100 billion in monitoring the kilogram standard by FY2001. [NES]*

AC Voltage and Current

The next quantities checked in Table 8 are ac (time-varying) voltage and current, for which improved accessibility and improved accuracy are needed. These ac quantities are important because, without them, most services provided by electronic and electrical systems would not be possible. Examples are digital computing, wireless communications, and electric-power distribution. The ac values are measured by comparison to dc (steady) values because dc values can be measured very accurately. However, a loss of accuracy occurs in the comparison. Further, the process used for the comparison is expensive. EEEL will pursue two routes to improvement. The first will provide a less expensive method for making the comparison, to improve *accessibility*. It is described in Objective 1.2.

> ***Objective 1.2***: Improve accessibility to accurate measurements of ac voltage and ac current by developing a lower cost integrated-circuit device to relate ac quantities to dc quantities. *Performance Goal: Complete and test a device, suitable for industry adoption, by FY 2000. [LFQ]*

Industry will use these devices to calibrate high-performance instruments. If the costs of these devices can be reduced sufficiently, industry may be able to build them into the high-performance measurement instruments to assure continued accuracy with reduced need for costly calibrations.

The second route to improvement will provide a new method for generating ac voltages, to improve *accuracy*. It is described in Objective 1.3. This approach may lead to a new Measurement Reference Standard for ac voltage, based on the same superconducting effect used for the present Measurement Reference Standard for dc voltage. Superconductivity is enabling major measurement advances.

> ***Objective 1.3***: Improve the accuracy of ac voltage measurements by developing an ac-voltage source based on the same fundamental physics of nature used to provide the Measurement Reference Standard for dc voltage. *Performance Goal: Source operational with 1-volt output by FY 1999. [SUP]*

Capacitance

The last quantity checked in Table 8 is capacitance. It is important because it is one of three quantities that can be used to *impede*, and thus control, the flow of electrical current. For example, capacitance, when used with inductance, enables *tuning* television transmitters and television sets to specific channels by impeding the signals from all unwanted channels. The present Measurement Reference Standard for capacitance is already based on the fundamental physics of nature, but its use is too laborious and thus too costly. The new approach in Objective 1.4 promises to reduce the labor required from months to weeks, for each use. It, too, is based on the fundamental physics of nature.

> ***Objective 1.4***: Improve accessibility of capacitance measurements by developing a new method for measuring capacitance, using the approach of the present Measurement Reference Standard for dc voltage, plus an electron-tunneling technique for determining electronic charge, both based on the fundamental physics of nature. *Performance Goal: Demonstrate working approach by FY 2003. [NES]*

Routes to Impacting Competitiveness

The improvements made to the measurement foundation for electrical quantities, in fulfillment of Goal 1, impact competitiveness through two principal routes.

Table 9: Mapping Measurement Foundation into Competitiveness by a First Route

Improved Measurement Foundation
↓
Calibration of instruments with higher performance at lower cost
↓
Better measurement support for R&D and manufacturing
↓
Realization of better product performance and quality at lower cost and better ability to prove product performance in the marketplace
↓
Improved competitiveness

The first route from the measurement foundation to competitiveness is through support of *high-performance measurement instruments*, as shown in Table 9. Such instruments directly benefit research, development, and manufacturing (especially process control). These, in turn, impact the competitiveness factors identified in Tables 1, 2, and 3.

The second route from the measurement foundation to competitiveness is through development of *application-specific measurement capability*. Such capability derives its *accuracy* from the measurement foundation, but extends *applicability* to specific industry problems that cannot be addressed with the measurement foundation alone. This extension is the subject of Goal 2, which is focused on the electronics industry, and of Goal 3, which is focused on the two electrical industries.

This extension must be made both for electrical quantities and for non-electrical quantities, such as length, to support these industries. This extension greatly increases the impact of measurement capability on competitiveness, and thus multiplies the benefits of the investment made in strengthening the measurement foundation through pursuit of Goal 1.

NSP 1.1
NSP 1.2

Goal 2: Provide Measurement Capability Required for a World-Class Electronics Industry

The electronics and electrical industries provide products that supply the basic services in Table 10. The electronics industry is principally focused on products that provide services related to information signals. These services are the subject of Goal 2. The electrical industries are focused on products and services related to electric power and energy. These products and services are the subject of Goal 3. Table 10 includes examples of the products associated with each basic service.

Table 10: Basic Product Services

Information Signals	
generate	laser diode
transfer	antenna, optical fiber
detect	sensor
process	microprocessor
display	liquid-crystal display
store	memory, disk drive
Power and Energy	
generate	generator
control	relay, switchgear
transfer	transformer, wire
convert	motor, lighting
store	battery

EEEL develops measurement capability that supports products performing all of the information-signal services in Table 10, including the products shown as examples. EEEL's development of application-specific measurement capability for these products impacts competitiveness through all of the mechanisms in Tables 1, 2, and 3. Needed measurement capability arises in all three families of electronic materials. These materials are the principal enablers of the functionality of electronic products: semiconductor (*semi*), optoelectronic (*opto*), and magnetic (*mag*). These materials are particularly critical to the services checked (✓) in Table 11.

Table 11: Enabling Materials for Information-Signal Services

		semi	opto	mag
generate	laser diode	✓	✓	✓
transfer	antenna, optical fiber		✓	
detect	sensor	✓	✓	✓
process	microprocessor	✓		
display	liquid-crystal display	✓	✓	
store	memory, disk drive	✓	✓	✓

The product characteristics in Table 2 are elaborated in Table 12 for reference in discussing specific EEEL Objectives below. The electronics industry pursues the desirable characteristics in Table 12 through many means, especially: (1) miniaturization, accomplished principally through integrated circuits (*int*); (2) higher frequencies (*hfq*); and (3) digital techniques (*dig*). The checks (✓) in Table 12 map progress in these key means into the factors that advance competitiveness. The three means are interdependent; progress in one may enable progress in others. The discussion below shows how EEEL's Objectives facilitate industry's efforts to realize the desirable product characteristics in Table 12, and thus competitiveness. First, measurement needs for integration are addressed, since integration advances all information-signal services in Table 10. Then, measurement needs beyond integration are addressed for three services: display, store, and transfer.

Table 12: Mapping Key Means Into Product Characteristics for Competitiveness

	int	hfq	dig
Performance			
higher information capacity	✓	✓	✓
higher information fidelity	✓	✓	✓
higher information density	✓		
higher energy efficiency	✓		
decreased size and weight	✓	✓	
Quality/Reliability			
fewer defects on delivery	✓		
fewer failures during use	✓		
Compatibility			
improved interfacing	✓		✓
reduced electromagnetic interference		✓	✓

Integration

Integration is fundamental to competitiveness in electronic products. NIST has launched an agency-wide effort to provide measurement capability to facilitate industry's success. The resulting National Semiconductor

Metrology Program focuses on semiconductor products; they are the first to push the science in pursuit of the highest levels of integration. Later, other miniaturization technologies will benefit. Some of the most important challenges to improving integration are shown in Table 13.

Table 13: Integration Challenges

Higher Fabrication Productivity
smaller circuit elements
bigger wafer sizes

Higher Fabrication Yield
purer input materials
better processes

Higher Frequencies
microwave circuits
optoelectronic circuits

Higher Fabrication Productivity

Integrated circuits are fabricated, many at a time, in arrays of rows and columns across the surfaces of thin, very flat, round "wafers" of silicon. Fabrication productivity can be increased by making individual integrated circuits smaller, so that more of them can fit on each wafer. This requires making *all* of the circuit elements smaller, including the transistors, their internal insulating materials, and the "wiring" interconnections. The resulting greater "device density", which is already doubling every two to three years, lowers costs and facilitates improving most of the *performance* characteristics in Table 12. However, achieving greater device density requires better application-specific measurements. EEEL responds in Objectives 2.1 to 2.3.

> ***Objective 2.1***: Develop improved measurements for making thinner insulating layers in transistors in integrated circuits, and for identifying better insulating materials, with thicknesses down to at least 2 nanometers. *Performance Goal: Measurement methods published by FY 2001. [SEM]*

> ***Objective 2.2***: Support accuracy of industrial linewidth standards used for accurate calibration of lithography tools for making element sizes down to 100 nanometers. *Performance Goal: Technical support provided for industrial development, and method of "tracing accuracy" to NIST placed in service, by FY 2001. [SEM]*

> ***Objective 2.3***: Develop laser power and energy measurements to support ultraviolet lasers operating at 193 nanometers, capable of imaging smaller elements in optical lithography processes. *Performance Goal: Calibration services implemented by FY 1999. [OPT]*

Fabrication productivity can also be improved by increasing the size of the wafers, so that more integrated circuits can be made on each wafer simultaneously. Larger wafer sizes require improved measurements for flatness, since flatness must be maintained over a larger area.

> ***Objective 2.4***: Develop measurements for the flatness and thickness of wafers as large as 300 millimeters, with measurement uncertainties of only 2 nanometers. *Performance Goal: Measurement service available by FY 1999. [NSM: Conducted in NIST's Manufacturing Engineering Laboratory.]*

Higher Fabrication Yield

Reducing fabrication costs requires high "yield", which means the percentage of *working* integrated circuits resulting from fabrication. Fabrication processes are disturbed by even small levels of contamination and even small departures from desired chemical composition. In particular, input materials, such as process gases, must be free of water vapor. Also, surfaces of integrated circuits must be inspected for contaminants and desired constituents to support process development and trouble shooting.

> ***Objective 2.5***: Develop a water-vapor source for use in calibrating equipment that can detect water vapor in inert processing gases at levels 500 times lower than now. *Performance goal: Calibration service implemented by FY 1999. [NSM: Conducted in NIST's Chemical Science and Technology Laboratory.]*

Objective 2.6: Develop a measurement method for detecting the presence and concentrations of desired and undesired atomic elements in integrated circuits with increased speed and accuracy, using a superconducting x-ray detector. *Performance Goal: Commercial implementation of measurement method by FY 2000. Within EEEL's span of influence, but outside EEEL's span of control. [SUP]*

Higher Frequencies

Semiconductor integrated circuits must operate at ever higher frequencies to achieve higher information capacity in computer circuits, to support expanding applications of wireless communications and local radar, and to avoid congestion at lower frequencies. At these higher frequencies, extending into the microwave region above 1 gigahertz, the elements of integrated circuits behave differently; new measurement capability is needed to determine performance and support product development.

Objective 2.7: Develop measurement methods for determining the microwave properties of thin insulating films in single, conducting lines on integrated-circuit substrates. *Performance Goal: Measurement method and accompanying software published by FY 2000. [RFQ]*

Increasingly, optoelectronic components are being fabricated as integrated circuits, too. They offer special capabilities, such as the ability to emit light. Epitaxial deposition is an important fabrication technique for making optoelectronic components, such as vertical-cavity surface-emitting lasers (VCSELs), used as light sources for local-area fiber-optic networks. However, control of fabrication processes, especially while they are occurring (real-time), is presenting major measurement challenges.

Objective 2.8: Provide data and real-time measurement methods for controlling the thickness and composition of layered structures during their growth by epitaxial deposition. *Performance Goal: Measurement methods for thickness and composition documented by FY 2000. [OPT]*

Display

The use of flat-panel liquid-crystal displays is essential for competitiveness in portable computers and portable video products and is becoming increasingly important for competitiveness in freestanding computer monitors. The United States is not a significant manufacturer of these displays, so the principal need is for measurements for use by U.S. manufacturers as buyers of displays.

Objective 2.9: Provide measurement methods for display performance for use by industry in specifying, evaluating, and purchasing flat-panel displays for computer and video products. *Performance Goal: Comprehensive flat-panel display measurement standard completed by industry by FY 2001. Within EEEL's span of influence, but not within EEEL's span of control. [VID]*

Successful products with video capability must employ sophisticated *digital* compression techniques to reduce the tremendous amount of data that must be transmitted and stored to support moving images. Objective measurement methods for evaluating these techniques are presently lacking.

Objective 2.10: Facilitate industry's evaluation of video compression techniques, by providing objective measurement methods for image degradation caused by compression. *Performance Goal: Test patterns and metrics completed by FY 2001. [VID]*

Store

Storage of information signals is accomplished by three principal methods: (1) semiconductor memory in the form of semiconductor integrated circuits, supported by the measurement efforts described above in the section on "Integration"; (2) optical disk drives discussed below; and (3) magnetic disk drives, also discussed below. All three methods employ *digital* techniques.

For optical disk drives, industry must achieve greater information capacity to remain competitive. To do this, industry needs more accurate measurements of the performance of the laser diodes used for "read" and "write" actions in these drives. The same measurement capability will also support pursuit of broader applications for laser diodes; an example is the sensing of pollutants.

> ***Objective 2.11***: Provide measurement support for laser power and energy at selected wavelengths not presently supported in the wavelength range of 400 to 1700 nanometers. *Performance Goal: Calibration services available by FY 1999. [OPT]*

For magnetic disk drives also, pursuit of greater information capacity is critical to competitiveness. At present, information density in magnetic disk drives is increasing at a rate of 60 percent per year. To support further advances, measurement reference materials are needed for calibrating the special microscopes that industry uses to develop products employing ever smaller magnetic patterns.

> ***Objective 2.12***: Support increased information density (bits per unit area) in magnetic disk drives by developing a series of measurement reference materials containing magnetic patterns of accurately known dimensions in the vicinity of 1 micrometer. *Performance Goal: Measurement reference materials completed by FY 2000. [MAG]*

For magnetic disk drives, higher information transfer rates, based on *higher frequencies* for reading and writing, are also a major factor in competitiveness. Especially needed are measurement methods for determining the time required to magnetize (switch) the individual bits (1 or 0) of information.

> ***Objective 2.13***: Develop a measurement method for switching times in magnetic materials with resolution of 0.1 nanosecond to support data rates of 1 gigabit per second or higher, versus the present 100-200 megabits per second. *Performance Goal: Measurement method published by FY 2000. [MAG]*

Transfer

Optical-fiber communications systems are critical to the national infrastructure and are dependent upon continued advances in measurement capability to support improvements in performance, quality control, and compatibility for components. Especially needed are Measurement Reference Standards for the calibration of instruments that measure critical quantities.

> ***Objective 2.14***: Develop Measurement Reference Standards to support accurate measurement of (1) wavelengths of light, with focus on the 1280-1560 nanometer range, to support wavelength-division multiplexing for increased information capacity; and (2) propagation characteristics critical to specifying the information capacity of an optical fiber. *Performance Goal: New Measurement Reference Standards issued by FY 2000. [OPT]*

The emergence of new microwave products, such as roadside communications, vehicle anti-collision radar, and automatic traffic-light controls, motivate the use of *higher frequencies* from 75 to 100 gigahertz. These higher frequencies are less used and offer special properties such as controllable range to minimize interference with other nearby systems. New measurement capability is needed to support the development of the antennas required for the new applications.

Objective 2.15: Develop the facilities and methodology needed for near-field scanning antenna measurements in the region 75-100 gigahertz. *Performance Goal: Facility improvements and methodology implemented by FY 2000. [RFQ]*

NSP 1.3

The emergence of more electronic products emitting electromagnetic signals has increased the need to assure that products with critical electronic components, such as motor vehicles, are not susceptible to harmful interference. International standards for susceptibility testing are particularly needed.

Objective 2.16: Provide technical support in pursuit of U.S. and international acceptance of reverberation-chamber measurements as a standard method for compliance testing for electromagnetic susceptibility. *Performance Goal: Domestic and international acceptance realized by FY 2000. Within EEEL's span of influence, but outside EEEL's span of control. [EMC]*

NSP 1.1
NSP 1.2

Goal 3: Provide Measurement Capability Required for World-Class Electrical Industries

Table 14: Basic Power and Energy Services

		eff	rel	equ	env	pq
generate	generator	□			□	
control	relay, switchgear	⊡	⊡		□	□
transfer	transformer, wire	⊡	□	⊡	□	
convert	motor, lighting	⊡	□	□	□	□
store	battery	□			□	

The measurement needs of the electrical-equipment industry are driven by many of the same competitiveness factors that apply to the electronics industry. The electrical-equipment industry supplies equipment to the automotive industry, the appliance industry, and virtually every other manufacturing industry. However, the electrical-equipment industry has an additional dimension, because it also provides equipment to the electric-power industry, which is a service industry that plays an especially critical role in the national infrastructure. The result is that the driving forces influencing these two electrical industries are usefully considered together and as a *combination* of competitiveness challenges and broader national challenges. Table 14 expands on the lower half of Table 10 by showing the principal points of intersection between basic power and energy services and national challenges. The challenges are energy efficiency (eff), the reliability and stability of the national power system (rel), equity in revenue metering (equ), environmental quality (env), and power quality (pq). The intersection of these with the services are indicated by the presence of a box (□), with or without a dot (•) in it. EEEL has provided measurement capability helpful in addressing many of these challenges. Each intersection in Table 14 that is the subject of EEEL work described below is marked with a dot in the box (⊡). Deregulation is being introduced to realize the benefits of domestic competition. It will give customers a choice of providers, based on market concerns, such as price and quality of service. Deregulation, and its implications for needed measurement support, are examined in detail in EEEL's study of the electric-power industry, listed in Table 5. In Objectives 3.1 through 3.3 below, EEEL is responding by providing measurement capability helpful in addressing (1) equity in revenue metering; (2) control of the power network to assure reliability and stability; and (3) energy efficiency in use.

Equity

Under deregulation, electricity will be generated by more providers and will be delivered to users through a *shared* transmission and distribution system, just as shared highways and railways enable moving merchandise. Accurate revenue metering, at a greater number of sites, will be needed to track ownership and to support equitable volume billing for electricity moving through the shared system. In response, industry has developed electronic watthour meters with higher accuracy over wider ranges. Calibrations from NIST are needed to validate accuracy and assure acceptance.

Objective 3.1: Develop new capability to support the calibration of electronic watthour revenue meter standards that provide high accuracy at five times the voltage and twenty times the current of earlier designs. *Performance Goal: Build and validate needed capability by FY 2000. [PWR]*

Reliability and Stability

The national electric-power system will become more complex, and thus more challenging to control, under deregulation. Particularly important are improved measurement sensors for providing the data needed by control systems to assure the reliability and stability of the system. Optical sensors for electrical quantities are especially promising. These sensors resist interference, interface readily with optical-fiber communications systems for transfer of data to control systems, and enable more measurements at more locations throughout the electric-power system.

Objective 3.2: Establish the feasibility of using optical sensors to achieve improved accuracy and accessibility in a new Measurement Reference Standard for ac current, and in electrical measurements made throughout the national electric-power system. *Performance Goal: Develop and test calibration procedure for optical current sensors by FY 2000. [PWR]*

Efficiency

Power distribution transformers perform the last voltage reduction just before the delivery of electricity to end users. High efficiency in these transformers is essential to the overall efficiency of the electric-power system. Similarly, motor efficiency is critical; more than half of all electricity generated is ultimately used by motors.

Objective 3.3: Validate, or improve as necessary, measurement methods and statistical sampling protocols for determining the energy efficiency of power-system distribution transformers (35,000 volts and below) and large motors (greater than 1 horsepower or 746 watts). *Performance Goal: Publication of method and protocol by FY 1999. [PWR]*

NSP 1.1
NSP 1.2

Goal 4: Provide Technical Support to Law Enforcement

EEEL manages a special NIST-wide program, authorized by the Congress, that supports the criminal-justice community. That community includes law enforcement, corrections, crime laboratories, fire services, and the court system. This program exploits the measurement and standards capabilities of NIST in diverse fields of science and technology to benefit this community in several ways: (1) to reduce injury and loss of life in law enforcement encounters; (2) to improve the quality of justice and security by increasing the reliability of techniques used for investigations and identification; and (3) to hold down the costs of public safety. This program is funded entirely by other Federal agencies, including the Departments of Justice and Transportation, and the Executive Office of the President. Upcoming Objectives, focused on reduction of loss of life, are described below.

Objective 4.1: Support reduction of loss of life in law enforcement encounters by incorporating a performance-assurance protocol in a revision of the body-armor standard. *Performance Goal: Protocol* *developed and included in National Institute of Justice (NIJ) standard STD-0101.04 by FY 1999. Development is within EEEL's span of control; inclusion is within EEEL's span of influence only. [LES: Conducted by contractor.]*

Objective 4.2: Support reduction of loss of life by developing mathematical models, based on laboratory and field investigations, that aid in estimating injury caused by less-than-lethal technologies employing physical-impact weapons. *Performance Goal: Completion of NIJ technical report on use of the model to determine injury from blunt trauma by FY 2001. [LES: Conducted by U.S. Army and contractor.]*

STRATEGIES (how the Goals and Objectives will be achieved)

Resources (human, capital, and information)

EEEL's FY 1998 resources, and the link to Goals, are shown in Table 15. If these levels are continued to FY 2004 in constant dollars, they will support EEEL's goals to the extent described below. About 70 percent of EEEL's funding comes to NIST by direct appropriation. It supports work broadly beneficial to the national economy. The rest of EEEL's funding comes from "other agencies" and "other outside" organizations, as reimbursements for measurement services they require.

Goal 1: Resources are adequate for pursuit of core activity but are less than needed for advances to support innovative new technologies developed by industry. Goal 1 is EEEL's first priority, since strengthening the measurement foundation underpins all progress in measurements.

Goal 2: Resources are less than needed. This is EEEL's second priority. EEEL *can* address selected measurement needs of the electronics industry, including those in the Objectives. However, the broader needs are many times greater, based on EEEL's study of the electronics industry in Table 5, which integrated information from many key information resources, and on the roadmaps in Table 6, which are themselves key information resources. To make up the shortfall, EEEL will pursue budget initiatives and support from other Federal agencies when possible. To maximize leverage, EEEL focuses on electronic materials and components that are the basis for diverse electronic products.

Goal 3: Resources are less than needed. This is EEEL's third priority. EEEL can address selected measurement needs of the two electrical industries, including those in the Objectives. The broader needs are many times greater, based on EEEL's study of the electric-power industry in Table 5, which integrated many key information resources. To make up the shortfall, EEEL will pursue budget initiatives and support from other Federal agencies when possible.

Goal 4: Resources are adequate. All funding is provided by other Federal agencies and is adequate to the tasks requested of NIST.

Communication, Accountability, and Other Factors

Goals and Objectives are developed with the EEEL staff and managers, and are communicated during that process. This plan is published and posted on the Internet for other agencies, customer organizations, and the general public. EEEL managers and staff are held accountable through individual performance plans. No programs need to be altered for the Objectives to be achieved. No legislative changes are required.

Table 15: FY 1998 Resources Managed by EEEL

	Funding ($millions)				Staff	
Funds Spent Inside EEEL	Total	NIST	Other Agencies	Other Outside	Full Time Permanent	Other Paid
Goal 1: Strengthen Foundation for All Electrical Measurements	13	9	3	1	76	7
Goal 2: Provide Measurement Capability Required for a World-Class Electronics Industry	32	25	3	4	176	19
Goal 3: Provide Measurement Capability Required for World-Class Electrical Industries	2	2	-	-	12	1
Goal 4: Provide Technical Support to Law Enforcement	2	-	2	-	7	-
	49	36	8	5	271	27
Funds Spent Outside EEEL						
Goal 2: Provide Measurement Capability Required for a World-Class Electronics Industry	6	6	-			
Goal 4: Provide Technical Support to Law Enforcement	1	-	1			

All dollars rounded to nearest million.

FACTORS AFFECTING ACHIEVEMENT (external)

The most important challenge to EEEL is *keeping pace* with the growing number and complexity of measurement needs, as electronic and electrical technologies advance both rapidly and globally. One form of EEEL's response is to assist industry in developing roadmaps because they provide early warning of impending measurement needs. The roadmaps are shown in Table 6.

NIST faces considerable *technical complexity* in its work because NIST does *only* what industry cannot do for itself. EEEL responds by hiring able staff and by assisting NIST in planning the facilities required to support world-class research. Implementation of the NIST's Advanced Measurements Laboratory is the most important facilities improvement affecting the long-term health of EEEL's measurement program.

The world of written standards is changing. Written are standards generally developed by the private sector. They address product performance, quality, compatibility, and safety, among other topics. When embodied as international standards, they affect market entry and U.S. competitiveness. EEEL joins the rest of NIST in examining industry arguments for a different, and possibly increased role, for NIST in written standards, particularly when effective representation of U.S. interests in international standards bodies is at stake. If this direction is determined to be in the national interest, an increased and competing demand for NIST's resources will result.

PROGRAM EVALUATION

EEEL plans its program primarily through *prospective evaluation* of needs. EEEL continues to review program relevance throughout its own research-and-development stages in order to guide the work to a successful conclusion and to facilitate timely transfer to the user.

EEEL *monitors its outputs*: (1) reimbursed services such as calibrations services and sale of Measurement Reference Standards for calibrating instruments; (2) joint activities, such as participation in written-standards organizations, professional societies, trade associations, and cooperative research, used for discovery of needs and delivery of findings; and (3) communications, such as publications, conference presentations, and consultations, used for delivery of findings and discovery of needs.

EEEL's *output quality* is assessed in published documents each year by an outside panel of impartial experts from industry, government, and universities, convened by the National Research Council.

EEEL *measures outcomes* through economic impact studies which sample EEEL's work. The studies are conducted by outside contractors funded by NIST. The studies completed (c) since 1991 are shown in Table 16, along with those currently underway (u). The dates are the actual or anticipated completion dates. The findings of these studies help guide planning by indicating what types of contributions have proved especially helpful to industry. The impact studies also provide a measure of assurance that EEEL's overall process for the selection and conduct of its work is effective.

Table 16: Economic Impact Studies Completed and Underway

FY	Topic	Status
1991	electromagnetic compatibility	c
1992	semiconductors (electromigration)	c
1992	optical fibers	c
1995	power and energy	c
1999	microwave antennas	u
1999	semiconductors (power devices)	u
2000	optoelectronics (laser calibrations)	u
2000	measurement foundation (voltage)	u

Status: c = completed. u = underway