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Electronics and Electrical Engineering Laboratory

STRATEGIC PLAN
For Fiscal Years 2001-2006

Electronics and Electrical Engineering Laboratory

February 2001

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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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U.S. DEPARTMENT OF COMMERCE
Donald L. Evans, Secretary

NATIONAL INSTITUTE OF STANDARDS
AND TECHNOLOGY
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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, academia, 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 $500 billion of products each year. The electrical-equipment industry ships the better part of $100 billion of products each year. 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 the providers of materials, information services, and energy. 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 that provide measurement research and related services 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.) 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.

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.

In some of 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:

Displays	DIS
Electromagnetic Compatibility	EMC

Electronic Data Exchange	EDE
Law Enforcement Standards	LES
Low Frequency	LFQ
Magnetics	MAG
National Electrical Standards	NES
National Semiconductor Metrology	NSM
Optoelectronics	OPT
Power	PWR
Radio Frequency	RFQ
Semiconductors	SEM

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. All but two of the above programs are conducted primarily within EEEL, and they draw on skills from the other NIST laboratories as needed. The two conducted primarily outside EEEL are shown below along with their associated codes.

Law Enforcement Standards	LES
National Semiconductor Metrology Program	NSM

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

ACKNOWLEDGMENTS

The following individuals contributed to the content of this strategic plan. All EEEL staff contribute to the implementation of this plan.

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TABLE OF CONTENTS

LIST OF TABLES

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 in turn requires new technology. New technology 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 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 the 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

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. This plan shows how EEEL helps manufacturers address the challenges in Tables 1, 2, and 3 thus improve their competitiveness.

Table 2: Product Characteristics for Competitiveness

Performance
Quality and Reliability
Compatibility
Safety

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 high impact by addressing three economically significant industries. The estimated annual shipments of these industries for 2000 are shown in Table 4 to the nearest $100 billion. All told, industries with shipments with approximately $800 billion per year are the direct beneficiaries of EEEL's work.

Table 4: Shipments of Customer Industries (2000 estimates)

Industry	Shipments ($billions)
Electronics	500
Electric Power	200
Electrical Equipment	100
	800

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 1.8 million 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 value of all electricity that the providers 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 supports U.S. international trade by furthering international agreement on measurements. A key means of doing this is comparing EEEL's measurements with those of counterpart ` institutes in other nations. International 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.

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 that EEEL principally serves: the electronics industry and the electric-power industry.

Table 5: Measurement Assessments Published

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

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

Table 6: Industry Roadmaps and Sponsors

Roadmap	Sponsor
International 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
Electricity Technology Roadmap	Electric Power Research Institute

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 accurate measurement of all electrical quantities. 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 afforded or adopted. Finally, EEEL pursues *measurement applicability*, which is the translation of EEEL's measurement capability into forms applicable to specific needs. 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 maintained by EEEL.

Table 7: Aims for EEEL's Measurement Capability
Accuracy
Accessibility
Applicability

GOALS AND OBJECTIVES (and responsive Performance Goals)

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 or measures. 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: calibration. NIST *calibrates* a small number of high-performance measurement instruments provided by customer organizations. Calibration is done by comparing the measurement performance of the instrument against the Measurement Reference Standards. The instruments so calibrated 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 instrumentation used in commercial channels.

NIST's Measurement Reference Standards must have high enough accuracy to support the most demanding users, including those pursuing major innovations. 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 similar Measurement Reference Standards of comparable accuracy because the fundamental physics of nature is accessible to all.

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

Table 8: Measurement Foundation for Electrical Quantities	
Base Quantities	
	time
	length
✓	**mass**
	dc current
Electrical Quantities	
	dc voltage
✓	**ac voltage**
✓	**ac current**
	power
	impedance
✓	**capacitance**
	inductance
	resistance

Mass

In the world of measurements, 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 kilogram 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. Objective 1.1 addresses this situation by referencing mass to the fundamental physics of nature through quantum-based electrical phenomena.

> ***Objective 1.1***: Provide a time-invariant definition of mass, and increase the accuracy of the determination of the fundamental constants of nature which depend on mass, by developing a measurement system for mass that is based on the fundamental physics of nature. *Performance Goal: Achieve a long-term uncertainty of $1x10^{-8}$ kilograms/kilogram in monitoring the kilogram mass standard by FY2003. [NES]*

AC Voltage and Current

The next quantities checked in Table 8 are ac (time-varying) voltage and current. These ac quantities are important because, without them, most services provided by electronic and electrical systems would not be possible; examples include digital computing, wireless communications, and electric-power distribution. For many applications, improved accessibility or improved accuracy are needed for ac quantities. In general, ac quantities are measured by comparison to dc (steady) quantities because dc quantities can be measured very accurately. However, a loss of accuracy occurs in the comparison. Further, the process used for the comparison is expensive. EEEL has been pursuing two routes to improvement. First, EEEL has just completed development of a lower-cost integrated-circuit device, suitable for industry adoption, that relates ac quantities to dc quantities. Industry will use these devices to calibrate high-performance instruments *[LFQ]*. If the costs of these devices can be reduced sufficiently, industry may be able to build them into high-performance measurement instruments directly, thus assuring continued accuracy with reduced need for costly calibrations. Second, EEEL is improving the measurement of ac quantities by developing a new method for generating ac voltages, to improve *accuracy*. It is described in Objective 1.2. This approach may lead to a new Measurement Reference Standard for ac voltage, based on the same superconducting quantum effect (Josephson effect) used for the present Measurement Reference Standard for dc voltage.

Objective 1.2: Improve the accuracy of ac voltage measurements by developing an ac-voltage source based on the fundamental physics of nature through dependency on the Josephson effect. *Performance Goal: Demonstrate first operational source by FY 2001. [LFQ]*

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, television sets, and wireless devices more generally, 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 1.3 promises to reduce the labor required from months to weeks, for each use. It, too, is based on the fundamental physics of nature, in this case through dependency on the quantum phenomena of single-electron tunneling and the Josephson effect.

Objective 1.3: Improve accessibility of capacitance measurements by developing a new Measurement Reference Standard for capacitance that is simpler to use, less costly, and more transportable than the current Measurement Reference Standard, and that is also based on the fundamental physics of nature. *Performance Goal: Demonstrate working approach to new representation of the farad 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.

The first route 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.

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 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. A similar extension must also be made for non-electrical quantities, such as length, to support these industries. Extending the measurement foundation 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.

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

The products of the electronics and electrical industries provide a variety of basic services shown in Table 10. The table includes examples of the products associated with each basic service. The electronics industry is focused primarily on services related to information signals. These services are the subject of Goal 2. In contrast, the two electrical industries are focused on services related to electric power and energy. These rather different products and services are the subject of Goal 3.

Table 10: Basic Product Services

Information Signals	
generate	laser diode
control	optical switch
transfer	antenna, optical fiber
convert	sensor, detector
store	memory, disk drive
process	microprocessor
display	liquid-crystal display
Power and Energy	
generate	generator
control	relay, switchgear
transfer	transformer, wire
convert	motor, lighting, heater
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 that are the most important enablers of the functionality of electronic products. These materials are shown in Table 11: semiconductor (*semi*), optoelectronic (*opto*), and magnetic (*mag*). These materials are particularly critical to the services checked (✓) in the table.

Table 11: Enabling Materials for Information-Signal Services

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

The product characteristics in Table 2 are elaborated in Table 12 for reference in discussing the specific EEEL Objectives below. The electronics industry pursues the desirable product characteristics in Table 12 through many means, especially: (1) miniaturization, accomplished principally with integrated circuits (*int*); (2) higher frequencies (*hfq*); and (3) digital techniques (*dig*). The checks (✓) in Table 12 show how these means tie to the factors impacting 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 information services: display, store, and transfer.

Table 12: Mapping Key Means Into Product Characteristics for Competitiveness

	int	hfq	dig
Performance			
higher information rates	✓	✓	✓
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 with integration. The resulting National Semiconductor Metrology Program focuses on semiconductor products. Products based on semiconductor materials lead the way to the highest levels of integration. Later, products based on other enabling materials will benefit. Some of the most important challenges to improving integration are shown in Table 13.

Higher Fabrication Productivity

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

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 2.4.

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 industry's pursuit of new, thinner insulating materials for gate stacks by developing a suite of dielectric evaluation techniques for characterizing electrical breakdown and wear-out of those stacks. *Performance goal: Evaluation techniques completed by FY 2003. [NSM]*

Objective 2.3: 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 2.4: Develop laser power and energy measurements to support ultraviolet lasers operating at additional wavelengths in the 150-200 nanometer range, including 157 nanometers, to support imaging even smaller elements in optical lithography processes. *Performance Goal: Calibration services for wavelengths between 150 and 200 nanometers implemented by FY 2002. [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 2.5: Develop measurements for the flatness and thickness of wafers as large as 300 millimeters in diameter, with measurement uncertainties of only 2 nanometers. *Performance Goal: Measurement capability delivered in industry-specified form by FY 2001. [NSM: Conducted in NIST's Manufacturing Engineering Laboratory.]*

Higher Fabrication Yield

Reducing fabrication costs requires high "yield", that is a high 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, surfaces of integrated circuits must be inspected for contaminants and for desired constituents to support process development and trouble shooting. To assist in addressing these problems, EEEL has just completed development of 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 *[NSM]*. This method has been licensed to two companies for development of commercial instrumentation.

Higher Frequencies

Semiconductor integrated circuits must operate at ever higher frequencies to achieve higher information rates 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 to support product development. In response, EEEL has just completed development of measurement methods for determining the microwave properties of thin insulating films used within individual conducting lines on integrated-circuit substrates *[RFQ]*.

Increasingly, optoelectronic components are being fabricated as integrated circuits, too. Optoelectronic components offer special capabilities, such as the ability to emit light. Epitaxial deposition is an important fabrication technique for making many of these components, such as the 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. In response, EEEL has just completed development of data and real-time measurement methods for controlling the thickness and composition of layered structures during their growth by epitaxial deposition *[OPT]*. EEEL is now proceeding to develop additional support for these fabrication processes by providing measurement methods for source gas purity, which must be maintained at very high levels to assure working devices.

> ***Objective 2.6***: Provide data and measurement methods for the purity of source gases used in the growth of layered structures by epitaxial deposition to form optoelectronic components. *Performance Goal: Measurement methods for source gas purity documented by FY 2001. [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 desktop computer monitors. The United States is not a significant manufacturer of these displays; but U.S. manufacturers need special measurements to specify, evaluate, and purchase the displays.

> ***Objective 2.7***: Provide measurement methods for display performance for use by U.S. industry when 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 outside EEEL's span of control. [DIS]*

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; and (3) magnetic disk drives, discussed below. All three methods employ *digital* techniques.

Pursuit of greater information density is critical to competitiveness of magnetic disk drives. At present, information density in magnetic disk drives is increasing at a rate of 60 percent per year. To support further advances, Measurement Reference Standards are needed for calibrating the special microscopes that industry uses to develop products employing ever smaller magnetic patterns. EEEL has just completed development of a Magnetic Imaging Reference Sample (MIRS) containing magnetic patterns of accurately known dimensions in the vicinity of 1 micrometer *[MAG]*. Next, EEEL will address measurements methods capable of imaging magnetic patterns down to 10 nanometers.

> ***Objective 2.8***: Develop a magnetic resonance imaging measurement method capable of 10 nanometer resolution and quantitative measurements, rather than the qualitative measurements of other magnetic imaging approaches. *Performance Goal: Demonstrate working approach employing sensing elements in the form of cantilevers, fabricated as micro-electromechanical systems (MEMS)*, by FY 2002. *[MAG]*

Also, for magnetic disk drives, higher data transfer rates, based on *higher frequencies* for reading and writing, are also a major factor in competitiveness. Data transfer rates are currently increasing by about 40 percent per year. Especially needed are measurement methods for determining the time required to magnetize (switch) the individual bits (1 or 0) of information. In response, EEEL has just completed development of 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 *[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. EEEL has just completed development of Measurement Reference Standards to support accurate measurement of (1) wavelengths of light, with focus on the 1280-1560 nanometer range *[OPT]*. This work supports: (1) wavelength-division multiplexing for increased information capacity; and (2) propagation characteristics critical to specifying the information capacity of an optical fiber.

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

> ***Objective 2.9***: 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 2001. [RFQ]*

Microwave products are moving increasingly into the consumer domain, especially in the form of mobile and handheld communications devices for voice and data. As this transition takes place, both reducing costs and increasing energy efficiency (to maximize operating time on batteries) become paramount to competitiveness. Both of these aims are advanced by the use of non-linear components. They are less expensive and more energy efficient than the linear components relied on primarily to date. However, existing measurement capability for non-linear components is less than optimal to support product design and testing in industry. As a first step toward resolving this problem, EEEL needs to determine industry's existing measurement capability.

Objective 2.10: Establish industry's current capability for measuring the non-linear behavior of radio-frequency circuits, with a special emphasis on power amplifiers, through a measurement intercomparison employing a modeled non-linear verification device. *Performance goal: Complete intercomparison by FY 2002. Within EEEL's span of influence, but outside EEEL's span of control. [RFQ]*

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 2.11: 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 2001. Within EEEL's span of influence, but outside EEEL's span of control. [EMC]*

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. The electrical-equipment industry also provides equipment to the electric-power industry, which, of course, plays an especially critical role in the national infrastructure. 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 intersections of the challenges with the basic power and energy 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 factors, 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 and 3.2 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.

To support these, EEEL has just completed development of a new capability to support the calibration of electronic watthour meter standards that provide high accuracy at five times the voltage and twenty times the current of earlier designs. Next, EEEL will extend support to meters capable of accurate measurement in the presence of harmonics. Harmonics are unwanted electrical power at higher frequencies. Harmonics will become increasingly significant as the power grid becomes more complex.

> ***Objective 3.1***: Develop the technical capability required to support electronic watthour meter standards that provide high accuracy for measurements of electric power containing harmonics. *(Performance Goal: Build and test sampling system for harmonic power measurement by FY 2001.)*

Reliability and Stability

As the national electric-power system becomes more complex under deregulation, it will also become more challenging to control. Particularly needed are improved measurement sensors for providing the data required 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 fibers for transfer of data to control systems, and enable more measurements at more locations throughout the electric-power system. EEEL has just completed establishing the feasibility of using optical sensors to achieve improved accuracy in measuring ac current. Next, EEEL will seek to extend the dynamic range of the calibration support that it provides for these sensors. This improvement will support expanding applications of the sensors, particularly for bidirectional power measurements of independent suppliers, who are sometimes suppliers and sometimes consumers of electricity. They have high current output when producing electricity, but small current input when consuming electricity.

> ***Objective 3.2***: Extend calibration support for optical current sensors to current levels a factor of ten smaller than now to support current measurements of wider dynamic range. *(Performance Goal: Expand the calibration support by FY 2001.)*

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. In response, EEEL has just completed validation of the measurement methods and statistical sampling protocols needed to determine the energy efficiency of power-system distribution transformers operating at 35,000 volts and below.

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. For example, this program just completed a standard for stab- and puncture-resistant armor which has been issued by the National Institute of Justice. New work focuses increasingly on readiness for coping with the effects of weapons of mass destruction used by terrorists.

Objective 4.1: Support the Office of Domestic Preparedness and the Office of State and Local Domestic Preparedness Support in the fight against terrorist incidents involving chemical and biological weapons of mass destruction by developing *guidelines* for detection, decontamination, and personal-protection equipment for use by emergency first responders. *(Performance goal: Draft guidelines completed by FY 2001. Within EEEL's span of influence but outside EEEL's span of control.) Conducted jointly with the National Institute of Justice, the Interagency Board for Equipment Standardization and Interoperability, the National Institute of Occupational Safety and Health, the Occupational Safety and Health Administration, the U.S. Army Soldier and Biological Chemical Command, and the National Fire Protection Association.*

In addition, this program is exploring the next step in this effort: the development of *national standards* for detection, decontamination, and personal protection equipment for addressing weapons of mass destruction. This exploration involves a diversity of cognizant agencies and associations.

STRATEGIES (how the Goals and Objectives will be achieved)

Resources (human, capital, and information)

EEEL's Goals are repeated in Table 15, along with the resources applied to each in FY 2000. If these levels of resources can be continued in constant dollars, they will support pursuit of EEEL's goals to the extent described below. Seventy-three percent of EEEL's funding comes to NIST by direct appropriation. This funding 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: This is EEEL's first priority, since strengthening the measurement foundation underpins all progress in measurements. Resources are adequate for pursuit of core activity but are less than needed for advances to support innovative new technologies developed by industry.

Goal 2: 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. Resources are less than needed. 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: 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. Resources are less than needed. To make up the shortfall, EEEL will pursue budget initiatives and support from other Federal agencies when possible.

Goal 4: 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. EEEL programs, as presently designed, are suitable for achieving the Objectives stated here. No legislative changes are required to enable the achievement of those Objectives.

Table 15: FY 2000 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	9	7	1	1	44	6
Goal 2: Provide Measurement Capability Required for a World-Class Electronics Industry	37	28	6	3	169	24
Goal 3: Provide Measurement Capability Required for World-Class Electrical Industries	3	2	1	-	17	1
Goal 4: Provide Technical Support to Law Enforcement	3	-	3	-	14	-
	52	*38	*10	4	*243	31
Funds Spent Outside EEEL						
Goal 2: Provide Measurement Capability Required for a World-Class Electronics Industry	*9	8	1	1		
Goal 4: Provide Technical Support to Law Enforcement	*5	-	5	1		

All dollars rounded to nearest million. *Totals do not add due to rounding.

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 rapidly on a global basis. 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, now under construction, is the most important facilities improvement affecting the long-term health of EEEL's measurement program.

The world of written, or documentary, standards is changing. Written standards are 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 for many products. 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 an a different or increased role is determined to be in the national interest, then a competing demand for NIST's resources may 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 each year by an outside panel of impartial experts from industry, government, and universities, convened by the National Research Council, which publishes the findings.

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 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 (revenue metering)	c
1999	semiconductors (power devices)	c
2000	optoelectronics (laser calibrations)	c
2000	power and energy (deregulation)	c
2001	measurement foundation (voltage)	u

Status: c = completed, u = underway