NISTIR 6844

Electronics and Electrical Engineering Laboratory

STRATEGIC PLAN 2002

Electronics and Electrical
Engineering Laboratory

February 2002

NIST

National Institute of Standards and Technology
Technology Administration
U.S. Department of Commerce

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 its customer industries and communities: the electronics industry, the electrical industries, and the criminal-justice and public-safety communities. Comments on this plan are invited and should be sent to the following address:

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U.S. DEPARTMENT OF COMMERCE
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TECHNOLOGY ADMINISTRATION
Phillip J. Bond, Under Secretary for Technology

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
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Bibliographic Information

Abstract

The Electronics and Electrical Engineering Laboratory (EEEL) provides measurement capability of high impact focused primarily on the critical needs of the U.S. electronics and electrical industries, and their customers and suppliers. EEEL also provides measurement and standards that support the criminal-justice and public-safety communities. These several capabilities promote productivity, trade, and improved quality of life, safety, and security. All are part of the national infrastructure that helps attract and retain businesses and jobs in the United States. EEEL provides only what its customer need and cannot provide for themselves, for technical, economic, or other reasons. The beneficiaries include the public, industry, government, academia, and other organizations.

The supported electronics and electrical industries are highly important to the U.S. economy. The electronics industry ships $547 billion of products each year (2000). The electrical-equipment industry ships $100 billion of products each year (2000). The electric-power industry, a service industry, ships $227 billion of electricity each year (2000), and relies on the electrical-equipment industry for power equipment. 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 made to the supported industries and the nation. The projects selected result from close interaction with industry and government to identify the needs which, if met, would have the greatest potential benefit to the nation.

Keywords

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

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Crosswalk between EEEL's Organizations and EEEL's Programs

EEEL's organizations and programs are shown below. EEEL is composed of a headquarters, six divisions, and two offices. Together they contribute to four programs. The first of the four programs provides the foundation for all electrical measurements. The other three programs target key customer industries, or communities, needing specific services. The divisions conduct work with their own staff. The offices matrix manage programs that draw on staff throughout NIST and, in the case of the Office of Law Enforcement Standards, from outside NIST, too. The checkmarks indicate the organizational units that contribute to each program. FY 2001 funding levels for each program are shown at the bottom.

Organizations	Programs			
EEEL Headquarters William E. Anderson, Director Alan H. Cookson, Acting Deputy Director	**1** **Foundation for all Electrical Measurements**	**2** **Electronics Industry**	**3** **Electrical Industries**	**4** **Criminal Justice and Public Safety**
Electricity Division James K. Olthoff, Chief Barry A. Bell, Deputy Chief	✓	✓	✓	✓
Semiconductor Electronics Division David G. Seiler, Chief David L. Blackburn, Deputy Chief		✓		
Radio-Frequency Technology Division Dennis S. Friday, Chief		✓		✓
Electromagnetic Technology Division Richard E. Harris, Chief	✓	✓		✓
Optoelectronics Division Gordon W. Day, Chief		✓		
Magnetic Technology Division Alan F. Clark, Chief		✓	✓	
Office of Microelectronics Programs Stephen Knight, Director		✓		
Office of Law Enforcement Standards Kathleen M. Higgins, Director				✓
FY 2001 Funds ($ millions)	10	47	3	13

EEEL'S ROLE

Mission

The mission of the Electronics and Electrical Engineering Laboratory (EEEL) is to strengthen the U.S. economy and to improve the quality of life by providing measurement science and technology, and by advancing standards, primarily for the electronics and electrical industries.

The U.S. economy depends critically on new technology as the basis for new and better products. New technology requires supporting measurement science and measurement technology. By providing these, EEEL enhances productivity, facilitates trade, and improves the quality of life. Measurement science and technology are part of the national infrastructure that helps attract and retain businesses and jobs.

EEEL's principal customer industries are the electronics industry and the electrical industries. EEEL also serves the criminal-justice and public-safety communities. EEEL serves other government agencies, at all levels, and many other organizations. All services are designed to benefit EEEL's ultimate customer: the public. EEEL will drop everything else to meet an urgent need of the public.

Values

EEEL adheres to three principal values, in this order: integrity, impact, and excellence.

> Integrity is first because it governs the internal and external relationships that underpin all that EEEL does. Internally, integrity is essential to an efficient, successful, and equitable working environment for all employees. Externally, integrity with customers and other stakeholders is essential for gaining support for EEEL's programs and for realizing impact through adoption of results.
>
> Impact is EEEL's second priority. It indicates that EEEL exists to produce outputs that benefit the nation and the taxpayers.
>
> Excellence is EEEL's third priority since work of the highest quality, consistent with maximum impact, is always the goal. Impact precedes excellence to indicate that EEEL is not here to produce excellence *at any cost*; often EEEL's customers need a good solution now, not an excellent one later.

Uniqueness of Contribution

EEEL does only what others cannot do, or will not do, for economic, technical, or other reasons. This policy promotes economic efficiency and assures a complementary relationship with EEEL's customers. EEEL acts when its customers need EEEL's unique characteristics: (1) measurement expertise; (2) impartiality, often to gain acceptance of findings by all affected parties; (3) official imprimatur as the lead U.S. laboratory for measurements, often to gain domestic or international acceptance to facilitate trade; (4) long-range view; or (5) efficiency in carrying out work once for the benefit of all.

Pursuit of Productivity and Competitiveness

EEEL strengthens the U.S. economy by enhancing the productivity, and thus the competitiveness, of U.S. manufacturers. To be competitive, manufacturers must meet the challenges in Table 1. Success in addressing the first two challenges is largely dependent on manufacturers' 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 both productivity and competitiveness.

Table 1: Manufacturers' Challenges

- Research and Development
- Manufacturing
- Marketplace Exchange
- After-Sales Support

Focus on Economically Significant Industries

EEEL assures high impact by addressing economically significant industries, as shown in Table 4. Industries with annual shipments of $874 billion per year are the direct beneficiaries of EEEL's work.[1]

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.

Table 2: Product Characteristics for Competitiveness

- Performance
- Quality and Reliability
- Compatibility
- Safety

The electric-power industry is composed of the providers of electricity, whether independent or owned by investors, government, or cooperatives. The $227 billion shown in Table 4 is the retail value of all electricity that these providers sell in a year.

The electrical-equipment industry makes the 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, lights, and heating elements.

Table 3: Marketing Requirements for Competitiveness

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

The industries in Table 4 are enabling industries. All other industries, government agencies, and the public rely on these industries for critical products and services.

Support for International Agreements on Measurements

EEEL supports U.S. international trade by furthering international agreements on measurements. A key means of doing this is comparing EEEL's measurements with those of counterpart metrology 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

Table 4: Shipments of Customer Industries (2000 estimates)

Industry	Shipments ($billions)
Electronics	547
Electric Power	227
Electrical Equipment	100
	874

[1](a) Electronics data from Electronic Industries Alliance, *2001 Electronic Market Data Book*, p. 1 (2001). (b) Electric-power data from Edison Electric Institute, *EEI Advance Release*, p. 1 (2001). (c) Electrical-equipment data from National Electrical Manufacturers Association web site, showing approximately $92 billion in shipments in 1999 and a growth rate suggestive of $100 billion in 2000.

with their own suppliers and customers, both domestic and international, on product characteristics, so that sales can be completed.

Emphasis on Highest Impact Needs

EEEL determines the highest impact measurement needs requiring EEEL's assistance through workshops, surveys, studies, and visits to companies. EEEL benefits greatly from roadmaps developed by industry, including those in Table 5. The roadmaps lay out industry's plans for remaining competitive in future years. EEEL often helps industry translate these plans into the measurement capability that will be needed for their success.

Table 5: 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

Support for 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 6 and are highlighted throughout this plan. As its top priority, EEEL pursues measurement accuracy; above all, the United States relies on EEEL to provide the foundation for accurate measurement of all electrical quantities. EEEL also pursues measurement accessibility and measurement applicability, with equal priority. Accessibility means translating measurement capability into forms that are technically and economically accessible to users. Applicability means translating EEEL's measurement capability into forms applicable to more needs. That is, EEEL may translate capability for measuring a given range of a parameter to other ranges (for example, from 1 volt to 1 microvolt) or from one parameter to another (for example, from dc voltage to ac voltage).

Table 6: Aims for EEEL's Measurement Capability

Accuracy
Accessibility
Applicability

PROGRAMS

EEEL's organizational structure is composed of a headquarters, six divisions and two offices. Together they conduct four major programs.

Program 1: Foundation for All Electrical Measurements
Program 2: Electronics Industry
Program 3: Electrical Industries
Program 4: Criminal Justice and Public Safety

A crosswalk between EEEL's organizations and EEEL's programs is provided on page v. The first program focuses on strengthening the foundation for all electrical measurements. This program supports all U.S. industries and underpins the work in the next three programs. These other three programs provide measurement capability needed by each of EEEL's principal customers: the electronics industry; the electrical industries; and the criminal-justice and public-safety communities.

Each of EEEL's programs pursues a broad goal. In fulfillment of each broad goal, EEEL pursues a very large number of technical objectives. Throughout this plan, representative technical objectives are provided to illustrate the specific work that EEEL does.

Program 1: Foundation for All Electrical Measurements

Goal: Strengthen the foundation for all electrical measurements.

The foundation for all electrical 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 achieved 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 for 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.

Table 7: 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

The quantities most important to the foundation for electrical measurements are shown in Table 7. 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 productivity and competitiveness is discussed.

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. The mass standard is the weak member in the measurement foundation and limits the accuracy of measurements of mass, weight, electrical quantities, and other quantities, too. In Objective 1.1, EEEL addresses this problem 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 FY2004.*

AC Voltage and Current

The next quantities checked in Table 7 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 recently completed development of an integrated-circuit device, suitable for industry adoption, that relates ac quantities to dc quantities. Industry will use these devices to calibrate high-performance instruments. If the costs of these integrated-circuit devices can be reduced sufficiently, industry may be able to build them into high-performance measurement instruments directly. So doing would assure 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*. This effort is described in Objective 1.2. It 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 2002, generating levels below 1 volt as the first step.*

Capacitance

The last quantity checked in Table 7 is capacitance. It is important because it is one of three means of impeding, and thus controlling, 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. This new approach is also based on the fundamental physics of nature through dependency on two quantum phenomena: 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.*

Routes to Impact on Productivity and Competitiveness

The improvements made to the measurement foundation for electrical quantities benefit productivity and competitiveness through two principal routes.

The first route is through support of high-performance measurement instruments, as shown in Table 8. Such instruments directly benefit research, development, and manufacturing, especially process control. These, in turn, affect the competitiveness factors identified in Tables 1, 2, and 3.

Table 8: 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 productivity and 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 Program 2, which is focused on the electronics industry, and of Program 3, which is focused on the electrical industries. A similar extension must also be made for non-electrical quantities, such as length, to support these industries. Extending the applicability of 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 Program 1.

The products of the electronics and electrical industries provide a variety of basic services shown in Table 9. The right column in the table shows examples of the products associated with each basic service. The electronics industry provides services related to information signals, as shown in the top half of the table. These services are the subject of Program 2. In contrast, the two electrical industries provide services related to electric power and energy, as shown in the bottom half of the table. These products and services are the subject of Program 3.

Table 9: 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

Program 2: Electronics Industry

Goal: Provide measurement capability required for a world-class electronics industry.

EEEL develops measurement capability that supports products that provide all of the information-signal services at the top of Table 9, including the specific products shown as examples. EEEL's development of application-specific measurement capability for these products improves competitiveness through all of the mechanisms in Tables 1, 2, and 3. Special measurement capability is needed to support all three families of electronic materials that are the most important enablers of the functionality of electronic products. These materials are shown in Table 10: semiconductor (*semi*), optoelectronic (*opto*), and magnetic (*mag*). These materials are particularly critical to the services checked (✓) in the table.

Table 10: 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 11 for reference in discussing the specific EEEL objectives below. The electronics industry pursues the desirable product characteristics in Table 11 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 11 show how these means tie to the factors affecting competitiveness. The three means are interdependent; progress in one may enable progress in the others. The discussion below shows how EEEL's objectives facilitate industry's efforts to realize the desirable product characteristics in Table 11, and thus competitiveness. First, measurement needs for integration are addressed, since integration advances all information-signal services in Table 9. Then, measurement needs beyond integration are addressed for three information services: display, store, and transfer.

Table 11: 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 program, run by the Office of Microelectronics Programs, 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 12.

Table 12: 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 reduction is accomplished by making *all* dimensions smaller, both in the plane of the wafer and perpendicular to that plane. Affected, for example, are transistors, including their internal insulating materials, and the "wiring" interconnections between the transistors. 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 11. However, achieving greater device density requires better application-specific measurements. EEEL responds in Objectives 2.1 to 2.5.

This past year EEEL completed development of improved measurements to support making thinner oxides, down to 2 nanometers. Next, EEEL will establish traceability for such measurements. Also, EEEL will support measurement of the electrical properties of the thinner oxides.

> ***Objective 2.1***: Develop and evaluate prototype procedures for establishing traceability to NIST of first-level commercial suppliers of reference materials for oxide-film thicknesses down to 2 nanometers. *Performance Goal: Prototype procedures established by FY 2003.*

> ***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.*

This past year EEEL delivered the first prototype reference materials to support industrial linewidth standards used for accurate calibration of lithography tools for making circuit element with sizes down to 100 nanometers. Next, EEEL will provide a full set of such reference materials, refined for improved ease of use.

> ***Objective 2.3***: Provide suite of reference materials, offering improved ease of use, to support industrial linewidth standards used for accurate calibration of lithography tools for making circuit elements with sizes down to 100 nanometers. *Performance Goal: Reference materials provided to industry by FY 2002.*

EEEL is further aiding progress toward smaller element sizes by providing measurement support for lasers that use shorter wavelengths to achieve higher resolution in lithography processes. Recently, EEEL provided support for 193 nanometers, Next, EEEL will address 157 nanometers.

> ***Objective 2.4***: Develop laser power and energy measurements for ultraviolet lasers operating at 157 nanometers, to support imaging smaller elements in optical lithography processes. *Performance Goal: Calibration services for 157 nanometers implemented by FY 2003, consistent with requirements of the International Technology Roadmap for Semiconductors..*

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 2002. [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. In particular, surfaces of the silicon wafers used to make integrated circuits must be inspected for contaminants. Optical approaches can assist.

Objective 2.6: Develop optical measurement methods and supporting models employing light scattering for determining the size of particles as small at 70 nanometers in diameter on the surface of silicon wafers. *Performance Goal: Measurement capability completed by FY 2003. [Conducted in NIST's Building and Fire Research Laboratory and Physics Laboratory.]*

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 is extending measurement support to ever higher frequencies.

Objective 2.7: Develop electro-optical techniques to perform on-wafer measurements of electrical waveforms at frequencies up to 110 gigahertz, suitable for characterization of telecommunications components operating at data rates of 10 gigabits per second to 20 gigabits per second. *Performance Goal: Measurement capability completed by FY 2003.*

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 is a major challenge. Among the many difficulties are control of process gas purity and maintenance of correct composition in compound semiconductors.

Objective 2.8: 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 2002.*

Objective 2.9: Develop composition standards for a compound semiconductor material, AlGaAs, that is critical to the development of optoelectronic devices. *Performance Goal: Provide composition standards with relative mole-fraction uncertainty of ±2 percent or less by FY 2003.*

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 computers. 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. In response, EEEL has assisted the industry in developing the new *Flat Panel Display Measurement Standard*, published by the Video Electronics Standards Association. Next, EEEL will focus on key issues in display performance, one of which is color and luminance reproducibility.

Objective 2.10: Develop a transfer standard for quantifying reproducibility in measurement of color and luminance in displays, to support an interlaboratory comparison of measurement capability for these parameters. *Performance Goal: Provide transfer standard by FY 2002. [Conducted jointly with the NIST Physics Laboratory.]*

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 the 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, EEEL will address measurements methods capable of imaging magnetic patterns down to 10 nanometers.

> ***Objective 2.11***: 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.*

Noise is a factor ultimately limiting the dimensional reductions needed to obtain high information density in magnetic memory devices. In response, EEEL will develop noise measurements for one of the best performing technologies, which is based on giant magnetoresistance.

> ***Objective 2.12***: Develop a measurement method for high-frequency noise in submicrometer giant-magnetoresistive devices to assess the fundamental limits to size reduction. *Performance Goal: Demonstrate working approach by FY 2002.*

Transfer

Optoelectronic systems for transferring information signals depend on high-speed performance from both sources and detectors. The design of optoelectronic systems requires knowing both the magnitude and the phase of the response to optical waveforms (which together are called the "vector response"). Phase is presently the more difficult of the two to measure.

> ***Objective 2.13***: Provide a calibration service for optoelectronic phase, with capability to 110 gigahertz. *Performance Goal: Calibration service in place by FY 2003.*

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 110 gigahertz, and above. These higher frequencies are used less frequently 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. In response, EEEL is currently developing facilities and methodology needed to provide special test services for near-field scanning measurements of antennas operating in the region of 75 gigahertz to 110 gigahertz. Thereafter, EEEL will proceed to even higher frequencies.

> ***Objective 2.14***: Develop the facilities and methodology needed for antenna measurements using near-field scanning in the region of 75 gigahertz to 110 gigahertz. *Performance Goal: Facility improvements and methodology implemented by FY 2002.*

Objective 2.15: Develop the facilities and methodology required to provide special test services for antenna measurements from 110 gigahertz to 170 gigahertz. *Performance Goal: Services offered by FY 2004.*

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. Non-linear components are less expensive and more energy efficient than the linear components used 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 for characterizing these components.

Objective 2.16: 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.*

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 2.17: 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 2002. Within EEEL's span of influence, but outside EEEL's span of control.*

Program 3: Electrical Industries

Goal: Provide measurement capability required for world-class electrical industries.

The electrical industries, as describe here, are the electrical-equipment industry and the electric-power industry. 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 electrical-equipment industry and the electric-power industry face a number of broad national challenges in providing basic power and energy services. Table 13 expands on the lower half of Table 9 by showing the principal points of intersection between basic power and energy services (down the left side of the table) and national challenges (represented by the columns across the right side of the table). The national challenges are energy efficiency (eff), the reliability and stability of the national power system (rel), equity in revenue metering (equ),

Table 13: Basic Power and Energy Services

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

environmental quality (env), and power quality (pq). The intersections of the national challenges with the basic power and energy services are indicated by the presence of a box (□), with or without a dot (•) in it. EEEL is providing measurement capability helpful in addressing many of these challenges. The dots in the boxes (⊡) in Table 13 indicate which of these intersections are the subject of representative EEEL work described in the objectives below. Other EEEL work, not described here, addresses other intersections.

Two recent developments place a special premium on successfully addressing these national challenges: terrorism and the deregulation of the electric-power industry.

Minimizing the consequences of terrorist attacks on the U.S. electric-power system requires advanced sensing and control systems. These systems must be able to identify damaged parts of the power system quickly and to support restoring electricity to affected areas quickly.

Deregulation is being introduced to realize the benefits of domestic competition. It is intended to give customers a choice of providers, based on market factors, such as price and quality of service. EEEL has been endeavoring to understand the implications of deregulation for needed measurement support. Table 14 lists three special efforts that EEEL has made to improve that understanding. The first is an environmental and technical study of the needs. The second is a workshop conducted with industry and other experts to identify the key needs. The third is an economic assessment of the benefits of meeting the key needs. They guide upcoming EEEL work.

Table 14: Deregulation Inquiries

Measurement Support for the U.S. Electric-Power Industry in the Era of Deregulation (1997) *[study]*
Challenges for Measurements and Standards in a Deregulated Electric Power Industry (1999) *[workshop]*
Changing Measurement and Standards Needs in a Deregulated Electric Utility Industry (2000) *[study]*

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. In response, EEEL has just completed development of calibration capability providing high accuracy at five times the voltage, and twenty times the current, of earlier designs. Now, EEEL is focusing on extending 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. At the first step, EEEL has just completed development of the technical capability to support electronic watthour meter standards in the presence of harmonics. Next, EEEL will translate this capability into a calibration service.

Objective 3.1: Complete new automated system for electric power and energy measurements in the presence of harmonics, and implement calibration service for customer power and energy meters operating up to 100 amperes and 600 volts. *Performance Goal: Calibration service implemented by FY 2004.*

Reliability and Stability

As the national electric-power system becomes more complex under deregulation, it will also become more challenging to control. Also, as terrorist threats continue, the ability to restore proper functioning of the electric-power system after disruptions is of even greater importance. Responsive to both of these concerns are improved measurement sensors that provide the data required by control systems. 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 established the feasibility of using optical sensors to achieve improved accuracy in measuring ac current. Next, EEEL will 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. Such suppliers may supply, or consume electricity, at different times. Generally, they have high current output when producing electricity, but small current input when consuming electricity. The challenge lies in measuring the lower currents accurately.

> ***Objective 3.2***: Extend calibration support for optical current sensors to current levels a factor of ten smaller than now to support measurements of wider dynamic range. *Performance Goal: Expand the calibration support by FY 2002.*

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. Recently, EEEL 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. Next EEEL will develop a portable measurement system that will demonstrate the practicality of conducting efficiency measurements at transformer manufacturers' locations, as they seek to comply with the new efficiency requirements of the Department of Energy.

> ***Objective 3.3***: Develop a portable system for testing the efficiency of distribution transformers in order to demonstrate efficiency measurements at manufacturers' locations. *Performance Goal: Portable system in service by FY 2002.*

Program 4: Criminal Justice and Public Safety

Goal: Provide technical support for the criminal-justice and public-safety communities.

EEEL's Office of Law Enforcement Standards (OLES) manages a special NIST-wide program, authorized by the Congress. This program provides technical support to the criminal-justice and public-safety communities. The customers are shown in Table 15. This program exploits the measurement and standards capabilities of NIST, and the special capabilities of outside organizations, too, in diverse fields of science and technology. The aim is to support the customers in several ways: (1) to reduce injury and loss of life in law-enforcement encounters and public-safety responses; (2) to improve the quality of justice and security by

Table 15: OLES Customers

Criminal Justice	law enforcement
	courts
	corrections
	forensic science
Public Safety	fire services
	hazardous materials units
	emergency medical services
	first-responder community

increasing the reliability of the techniques used for investigations and identification; and (3) to provide for, and hold down the costs of, public safety. This program is funded entirely by other Federal agencies. The organizations currently providing either funds or assistance in kind (such as equipment) are shown in Table 16.

Table 16: Sources of OLES Resources

Funds
- National Institute of Justice
- National Highway Traffic Safety Administration
- Federal Aviation Administration
- Technical Support Working Group (interagency)
- Memorial Institute for the Prevention of Terrorism

Assistance in Kind
- Bureau of Prisons (DOJ)
- Defense Computer Forensics Laboratory (DOD)

The OLES program is undergoing major changes in the wake of the terrorist attacks on the United States in 2001. The likely implications are outlined in Table 17, expressed in terms of the environmental changes and their impact on OLES. Needless to say, a major expansion in the size of the OLES program is in the offing, accompanied by a shift of resources toward homeland-security activities in several parts of the program.

Table 17: Environmental Changes and Impact on OLES

Environmental Changes
- billions of government dollars to domestic preparedness equipment
- hundreds of new security/protection technologies coming to market
- strong demand for performance standards to govern marketplace exchange

Impact on OLES
- nearly a doubling of OLES budget to provide needed standards
- intensified collaboration within and outside NIST
- redirection of existing OLES programs for better match to homeland security

OLES responds to national needs with six major program elements, as shown in Table 18. Objectives 4.1 through 4.3 below provide three examples. They come from the checked program elements. The examples are particularly important to the current counter-terrorism effort.

Table 18: OLES Program Elements

- Weapons and Protective Systems
- ✓ Detection, Inspection, and Enforcement Technologies
- Chemical Systems and Materials
- Forensic Sciences
- Public Safety Communication Standards
- ✓ Critical Incident Technologies

Of key importance is detecting threatening individuals and their weapons. For detecting threatening individuals, OLES is providing support for the development of automated approaches to human recognition. The initial focus is on recognition of faces, but later efforts may address other characteristics, such as gait.

> ***Objective 4.1:*** Develop a database of faces to support development and testing of automated facial recognition systems. *Performance goal: Deliver database by FY 2002. [Conducted by NIST's Information Technology Laboratory.]*

Also important is the detection of weapons on individuals, especially from greater distances. Present magnetic technology is very short range and does not provide images. Microwave approaches promise both images and longer range.

> ***Objective 4.2:*** Develop monolithic microbolometer array for remote detection of concealed weapons on human beings by imaging reflections of gigahertz and terahertz waves. *Performance goal: Fabricate first array by FY 2002. [Conducted by EEEL's Radio-Frequency Technology Division.]*

Finally, the protection of the individuals who first respond to a dangerous crisis is of paramount importance. These individuals often cannot know what hazard they are about to face, so they must have diverse types of protection.

> ***Objective 4.3:*** Develop performance standards for chemical and biological protection, detection, and decontamination equipment for first responders. *Performance goal: Standards completed by FY 2004. Within EEEL's span of influence but outside EEEL's span of control because rate of progress dependent on provided funding levels.*

[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.]

RESOURCES

EEEL manages resources that are spent both inside and outside EEEL. These resources come from the NIST appropriation, other agencies, and other outside organizations. The resources, by program, for the most recently completed year, FY 2001, are shown in Table 19.

The column of four boldface numbers at the bottom center of the table indicates that EEEL's total investment is largest for Program 2 ($47 million), which supports the U.S. electronics industry. Second comes Program 4 ($13 million), which supports the criminal justice and public safety communities. Third is Program 1 ($10 million), which supports the foundation for all electrical measurements. Fourth, is Program 3 ($3 million), which supports the electrical industries.

Recall from the discussion above that increased support is anticipated for Program 4, so its position as the program with the second largest amount of resources will only be strengthened during FY 2002.

Table 19: FY 2001 Resources by Program

		Funds ($millions)				Staff	
		Total	NIST	Other Agencies	Other Outside	Full Time Permanent	Other Paid
Funds Spent Inside EEEL, and Staff							
1	Foundation for All Electrical Measurements	10	7	2	1	45	6
2	Electronics Industry	39	31	6	2	172	22
3	Electrical Industries	3	2	1	-	13	2
4	Criminal Justice and Public Safety	3	-	3	-	9	-
		*54	40	*11	3	239	30
Funds Spent Outside EEEL							
2	Electronics Industry	8	7	-	1		
4	Criminal Justice and Public Safety	10	3	7	-		
		18	10	7	1		
Funds Totals							
1	Foundation for All Electrical Measurements	**10**	7	2	1		
2	Electronics Industry	**47**	*39	6	*2		
3	Electrical Industries	**3**	2	1	-		
4	Criminal Justice and Public Safety	**13**	3	10	-		
		*72	*50	*18	*4		

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

STRATEGIC PLANNING

In June 1999, EEEL held an offsite meeting of managers and senior staff, modeled after the Baldrige process associated with NIST's Baldrige National Quality Program. At that meeting, the participants were asked to identify opportunities for improving EEEL. Of those opportunities identified, the participants placed the highest priority on strategic planning. The result was that EEEL developed a new strategic planning process. The six parts of this process are shown in Table 20. EEEL then began to implement this process, executing one part after another, while endeavoring to improve the process and to realize useful outputs. That effort continues to this day.

Table 20: Strategic Planning Process

Part	
1	Values
2	Mission and Role
2	Environmental Assessment
4	Strategic Review and Decision Making
5	Evaluation Criteria
6	Program Review and Decision Making

A key outcome of this process has been improved focusing of EEEL's program. This focusing was realized by a series of program stops and starts. Stops were implemented for a variety of reasons, such as these: work had been completed; work was not as important as other work; work was better consolidated elsewhere. Starts were implemented principally to help prepare EEEL for entry into areas of increasing concern or opportunity for industry or government. The programs and the specific technical areas affected are shown in Table 21.

Table 21: Program Focusing

Program	Stops
2	compound semiconductor growth
2	semiconductor packaging
2	measurements for complex electronic systems
3	plasma processing of gaseous dielectrics
3	inductive voltage divider calibration service
	Starts
2	bulk CMOS replacement technologies
2	single-molecule manipulation and measurement
2	metrology for microwave and millimeter-wave radiometry
2	metrology for wide-bandgap optoelectronic materials

PROGRAM EVALUATION

EEEL evaluates its impact in a variety of ways.

EEEL *monitors many categories of 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. The panel publishes its findings, and EEEL responds to those findings in detail.

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, or presently underway (u), are shown in Table 22. 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 22: 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)	c
2002	supply chain integration infrastructure	u

Status: c = completed, u = underway