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EMERGING TECHNOLOGIES IN ELECTRONICS

...and their measurement needs

Second Edition

**Prepared by the Managers
and Staff of the Center for
Electronics and Electrical
Engineering**

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

February 1990

**U.S. DEPARTMENT OF COMMERCE
Robert A. Mosbacher, Secretary
Lee Mercer, Deputy Under Secretary
for Technology
NATIONAL INSTITUTE OF STANDARDS
AND TECHNOLOGY
John W. Lyons, Director**



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What's New in the Second Edition?

New chapters are included on lasers, optical fiber sensors, video technology, and electromagnetic compatibility. Major changes have been made to the overview and to the chapters on semiconductors, superconductors, and optical fiber communications. These changes provide more information about the relationships among the emerging technologies, the motivation for new programs of measurement support, and the structure and technical details of those programs.

Preface

The National Institute of Standards and Technology provides measurement capability needed for the success of emerging technologies critical to U.S. competitiveness. This report presents an assessment of the most important measurement needs in several key electronic technologies. The report is designed to solicit feedback from U.S. industry and Government that will guide the Institute in its support of industrial research and development, manufacturing, marketplace access and exchange, and the use of the nation's high technology products.

John W. Lyons, Director

EMERGING TECHNOLOGIES IN ELECTRONICS

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Chapter 1 OVERVIEW

Introduction

Powerful technologies are emerging in many fields of electronics. They promise new generations of products with higher performance and lower cost. U.S. success in realizing products from these emerging technologies is vital to U.S. competitiveness in key world markets.

U.S. competitiveness in emerging technologies requires a high level of supporting measurement capability. That capability affects every phase of product realization: research and development, manufacturing, marketing, and use. For example, available measurement capability influences: the pace and success of research and development in creating high performance products; the design and implementation of advanced manufacturing processes capable of producing products with high quality and low cost; the specification and proof of performance of products in the marketplace; and the installation and maintenance of products after sale. A high level of measurement capability benefits manufacturers of high technology products, buyers of high technology products, and users of the services of those products. Affected are the U.S. Government, companies, universities, and individuals.

The National Institute of Standards and Technology (NIST) is the nation's lead organization for the development of measurement capability and for the maintenance of national reference standards that assure the uniformity of that capability. Within NIST, the Center for Electronics and Electrical Engineering (CEEE) is responsible for measurements that support the U.S. electronics industry. As part of fulfilling this responsibility, CEEE assesses measurement needs that affect the competitiveness of the U.S. electronics industry in emerging technologies. This report is the second in a series that seeks to provide an increasingly comprehensive assessment of those needs. Through issuance of this report, CEEE seeks feedback from U.S. industry and from Government agencies to help refine the assessment of those needs and to guide future programs of measurement support responsive to those needs.

Identification of the Emerging Technologies in Electronics

CEEE has identified emerging technologies that fall within seven fields of electronics: semiconductors, superconductors, magnetics, lightwaves, microwaves, video technology, and bioelectronics. The specific emerging technologies within each field are listed under the field names in Table 1. CEEE defines an emerging technology as one that is new to the marketplace or that is undergoing fundamental change.

In addition, CEEE has identified three major challenges that are facing all emerging electronic technologies: electromagnetic compatibility, testing of complex systems, and standardization of descriptions of complex systems. These challenges are listed at the bottom of Table 1.

The first column in Table 1 indicates if CEEE has a present FY 1990 program to provide some measurement capability for each emerging technology. The second column indicates if CEEE believes that additional measurement capability is required for each emerging

technology. The third column indicates if CEEE has included in this report a chapter that documents the new measurement capability needed and that describes a plan for providing that capability.

Note that CEEE has not yet developed plans for measurement support for all of the emerging technologies identified in Table 1. CEEE will work steadily toward that goal in future editions of this report. Also, for some emerging technologies, such as those in the fields of semiconductors and superconductors, CEEE has described just the first phase of needed measurement support. More comprehensive descriptions will follow.

The measurement requirements of many of the emerging electronic technologies are very broad and will require capabilities from throughout NIST for resolution.

NIST's role in developing measurement capabilities responsive to the needs of U.S. industry is described in Chapter 11.

Summary of the Emerging Technologies in Electronics

The following sections summarize, by field, the emerging electronic technologies that CEEE has identified to date. The summaries stress what is new or different about each of the emerging technologies. The technologies are discussed in the order listed in Table 1.

Semiconductors

Two near-term emerging technologies fall in the field of semiconductors. High density silicon integration is moving to reduced internal device sizes, increased integrated circuit density, and increased device speed. Internal device sizes are now typically a few micrometers and will be reduced by a factor of 10 to about 0.1 micrometer with an attendant increase in circuit density of a factor of 100. Compound semiconductors, such as gallium arsenide, are emerging to provide high-speed transistor devices, high-speed integrated circuits for microwave and computer technologies, and powerful optoelectronic components. Compound semiconductors are the only semiconductors that can produce light.

In addition, several other emerging technologies are on the horizon. They are listed here but are not addressed further in this report. They include: quantum confinement devices made from compound semiconductors, with characteristic sizes of 0.01 micrometer or less, and with speeds possibly 1000 times faster than present devices; vacuum microelectronic devices which offer dazzling speeds and show promise for flat screen color displays of high resolution and high brightness; diamond semiconductors which can operate at very high temperatures for greater environmental tolerance and reduced cooling problems; high efficiency photocells which extract virtually all of the electrical energy that can be obtained from the sun by devices of a given size; and speculative semiconductor micromachines with potential applications in prostheses and in sensing.

Table 1
Emerging Technologies in Electronics
 Present and New NIST Programs of Measurement Support

<u>Field / Emerging Technology</u>	<u>Present FY 1990 Program</u>	<u>New Measurement Capability Needed?</u>	<u>Needed Measurement Capability Documented?</u>
Semiconductors			
High Density Silicon Integration	yes	yes	Chapter 2
Compound Semiconductors	yes	yes	Chapter 2
Superconductors			
Low Temperature	yes	yes	no
High Temperature	yes	yes	Chapter 3
Magnetics			
High Density Information Storage	yes	yes	Chapter 4
Magnetic Sensing	yes	yes	Chapter 4
Advanced Magnets	yes	yes	Chapter 4
Lightwaves			
Optical Fiber Communications	yes	yes	Chapter 5
Optical Fiber Sensors	yes	yes	Chapter 6
Lasers	yes	yes	Chapter 7
Optical Information Storage	no	yes	no
Optical Signal Processing and Computing	no	yes	no
Microwaves			
High Performance Individual Components and Antennas	yes	yes	Chapter 8
Integrated Circuits	yes	yes	Chapter 8
Integrated Antennas	no	yes	Chapter 8
Video Technology			
High Resolution Vision	no	unknown	no
Real Time Signal Processing	no	yes	Chapter 9
High Data Rate Transmission	yes	yes	Chapters 5,8,9
High Density Information Storage	yes	yes	Chapters 4,9
High Resolution Displays	no	yes	no
Bioelectronics			
	no	not yet	no
Challenges to Emerging Technologies			
Electromagnetic Compatibility	yes	yes	Chapter 10
Complex System Testing	yes	yes	no
Complex System Description	yes	yes	no

Superconductors

The discovery of high temperature superconductors has spurred interest in both low and high temperature superconductors. Low temperature superconductors are delivering high current levels in magnets for large scale applications, such as magnetic resonance imaging, fusion research, and the upcoming Superconducting Super Collider (SSC). Low temperature superconductors are also delivering extraordinarily high speeds, high accuracy, and high sensitivity for electronic applications in deep space listening, precision waveform measurement, and national electronic standards. However, low temperature superconductors exact the cost of operation at liquid helium temperatures. High temperature superconductors offer operation in liquid nitrogen which is less expensive and much easier to handle. High temperature superconductors have already been fabricated as elemental electronic devices capable of high sensitivity and speed. They have not yet been fabricated as wires capable of carrying the high current levels required for many practical applications. However, the problems that they pose may be overcome, just as they were for the low temperature superconductors. At stake are new products for electric power systems, computers, medicine, transportation, and research.

Magnetics

Magnetics is advancing on three major fronts. High density information storage systems are breaking all records for fast access times and low cost. Further advances will be necessary for them to cope with even higher information demands from emerging applications, such as advanced video technology including high definition television. Magnetic sensing is moving to a new level of sophistication and to broadened applications in medicine, geomagnetic prospecting, submarine detection, and assessment of critical structures such as aircraft frames and surfaces. Advanced magnets and other magnetic materials, including specialty alloys and "magnetic glasses", promise higher efficiency, lower weight, and lower cost for motors and generators. They also promise higher frequency operation for microwave electronic systems.

Lightwaves

Lightwave technologies are emerging at a rapid pace. Four are surfacing at the present time: Optical fiber communications are already providing long distance digital telephone and data communications. The first two trans-oceanic lines are now in service, with many more planned. Next will come second generation long-distance lines with a thousand times higher information capacity, and new local loops to bring high capacity and superb signal quality directly to homes and businesses. New services will become possible including high definition television and, possibly, on-demand text, video, and audio for unparalleled access to worldwide sources of information, with great promise for business and education. Optical fiber sensors offer high sensitivity, ruggedness, small size, and low cost to serve diverse applications in transportation, medicine, manufacturing, energy, and other fields. Embedded fiber sensors may enable truly "smart structures" for aircraft that can sense and avoid impending structural failures. Lasers are surfacing in diverse products for manufacturing, research, medicine, information storage, inventory control, and many other fields. They provide unprecedented precision and speed in the applications that they serve. For example, in manufacturing, lasers can drill precise holes with diameters smaller than a human hair; they are the tools that never dull. In medicine, lasers provide the least invasive of surgical procedures. Optical information

storage is yielding its first commercial products and is providing the highest information densities yet achieved in removable storage media for computers and automated office filing systems. These capabilities complement those of the new magnetic information storage systems that provide the highest access speeds. In the far term, optical signal processing and computing promise extraordinary speeds for many applications. In the most sophisticated implementations, high levels of intrinsic parallel processing will be applied for special applications, such as image processing.

Microwaves

Three near-term microwave technologies are emerging. High performance individual components and antennas, including miniature components, are emerging. They offer altogether new capabilities, smaller sizes, and higher operating frequencies to serve major national needs in communications, radar, weather forecasting, environmental sensing, and other areas. Integrated microwave circuits have a chance to become a commercial reality and to reduce the cost, improve the performance, and raise the operating frequencies of microwave systems. These advances will support promising new applications, such as signal processing for high definition television, vision systems for robots, anti-collision radar for automobiles, and advanced corporate and personal communications systems. Higher frequencies, higher data processing speeds, and higher data transfer rates, as much as 10 to 100 times present levels, will become accessible. The revolution that came earlier to computers and to other electronic systems through semiconductor integration will now come to microwave electronics. Integrated antennas will contain built-in signal transmitting and receiving electronics for superb control of signal direction and shape in compact antennas for applications in airplanes, automobiles, corporate facilities, satellites and other spacecraft, and even individual homes.

In the near term, all three of the above emerging technologies will reach frequencies of 100 GHz (100,000,000,000 Hz). In the far term, the latter two technologies will go on to reach frequencies of 1000 GHz.

Video Technology

Video technology, to date, has not been able to take full advantage of the extraordinary capabilities of human vision, the most effective sense for receiving information. Video systems have had to choose between high picture quality (high resolution) and smooth motion (large number of pictures per second), since video systems could not handle data fast enough to achieve both. Computers chose high quality, and television chose smooth motion.

Now with the emergence of advanced video technology and of powerful networking technologies, the capabilities of computers, television, and telecommunications systems can be progressively merged. This merger will produce a powerful new video window to the world that will provide corporations, governments, and individuals with entry to a new information age. If the prospect of on-demand services can also be realized through high information capacity networking systems, like those employing optical fibers, then users of new video technology will gain access to libraries of books, audio material, and video material whenever they wish.

Five near-term emerging video technologies will make all of this possible. High resolution vision systems (cameras, scanners, etc.) will capture images. Real time signal processing technology, operating at phenomenal speeds, will prepare the data for transmission and for display after reception. High data rate transmission systems, particularly optical fiber communications systems and microwave systems, will transmit the video images. High density information storage systems will store and play back video material; and high resolution displays, particularly flat panel displays, will display delivered images.

The new video technology will serve many applications in many fields, including business, education, entertainment, medicine, defense, security, transportation, publishing, advertising, and banking, among others. The potential applications are quite diverse and include: widespread availability of high quality teleconferencing; access to educational materials; electronic access to multiple newspapers with automated searching and color photographs; displays and vision systems for airplanes, for satellites, and for automobiles with unobstructed electronic rear-view mirrors and electronic maps; and high performance vision systems for robots.

Bioelectronics

Bioelectronics is a far-term emerging electronic technology. Ultimately, it may complement or replace some of the functions of semiconductor technology. New bioelectronic systems offer potential, yet to be assessed, for key advantages relative to semiconductor electronics: (1) self-assembly of circuits, that is, circuits that can actually be "grown"; (2) extremely small structures measuring possibly 50 nanometers, and constructed in three dimensions; (3) high computing speeds resulting from the fact that bioelectronic processes can handle so much information in a single step that even millisecond bioelectronic processes can beat nanosecond electronic processes; (4) high energy efficiency; (5) flexible biological interfaces that can connect with biological systems, including human beings; (6) new sensors that are capable of recognizing complex materials or patterns, such as sensors that can smell; (7) high reliability; and (8) intelligent functions through imitation of neural and intelligence patterns of biological systems to perform very complex functions.

It is too early to define a new program of measurement support for the emerging field of bioelectronics, but the prospects of the field merit continued close monitoring.

Challenges to Emerging Technologies

Emerging technologies in electronics face an increasing number of challenges that derive from their complex nature and mutual interactions. To realize the full benefits of the emerging technologies, these challenges must be addressed and resolved. Three of these challenges are described below.

As electronic systems proliferate, they tend to develop mutual interference which requires resolution of problems with electromagnetic compatibility. Many of these problems arise from the high sensitivity and low power requirements that made semiconductor electronics attractive in the first place.

As electronic systems become more complex, they become more difficult to test for proper performance, requiring new capabilities for complex system testing. The new capabilities must be so intelligent that they can assure high levels of confidence in proper system performance with far less than 100% testing. Ideally, progress in complex system testing should influence initial system design so that later testing is facilitated. The result can be dramatic improvements in the reliability of complex systems.

Complex systems pose significant challenges also in complex system description. One possible solution is the development of universal computer-based descriptions for the design and manufacture of components and systems ranging from transistors to battleships. These universal descriptions lead to software catalogs of standard parts for multiple applications and reduce the cost of design, modification, and maintenance of complex systems.

A Word about Smart Systems

Smart systems include those employing artificial intelligence, expert systems, neural networks, adaptive electronics, self-calibrating electronics, and a variety of other capabilities. These smart systems were listed as a separate emerging technology in the first edition of this report on emerging technologies in electronics. Since preparing that edition, CEEE has decided to address individual smart systems as parts of the other emerging technologies that they serve. For example, CEEE is addressing expert systems for controlling semiconductor processing as part of the field of semiconductors.

Relationships Among the Emerging Technologies

The emerging technologies in electronics are highly interdependent as shown in Figure 1. In that figure, lines are drawn from one field to another to indicate the direction of flow of support. A double line indicates a high degree of support, and a single line indicates a moderate degree of support. "Support" in this case means the incorporation of products from the supporting technology into products of the supported technology.

Semiconductor technology, more than any other technology, is the basis for the others. For example, high density silicon integrated circuits are used in virtually all of the other technologies. Compound semiconductors are critical to lightwave technology because they can produce light. They are also critical to microwave technology because of their high speed. Note, too, that semiconductor processing technology has been critical to many other technologies. For example, it provides the basis for many of the processes used to make low temperature superconducting integrated circuits; and it provides the techniques used for polishing magnetic recording media.

Superconductor electronics are used in emerging versions of magnetic sensing apparatus. Superconductor materials show promise for high performance microwave antennas for space borne applications. Superconductor electronics already provide the most sensitive microwave mixers known; these superconductor mixers are the first stage, and thus the most critical stage, of special microwave receivers like those used for deep space listening.

Lightwave and microwave technologies are mutually dependent. Microwave electronics provide signal processing circuits that are critical to emerging optical fiber systems with very high information capacity. On the other hand, optical fiber technology will be the key to new microwave antennas with unprecedented control of beam direction and radiation pattern. Further, optical fiber and microwave communications technologies are highly complementary. Optical fiber technology provides the highest information capacity available for communication between fixed locations. Microwave technology provides the highest information capacity available for communication with mobile units, including cars, airplanes, ships, and satellites; microwave technology also provides the most flexible means of communication available for both fixed locations and mobile units.

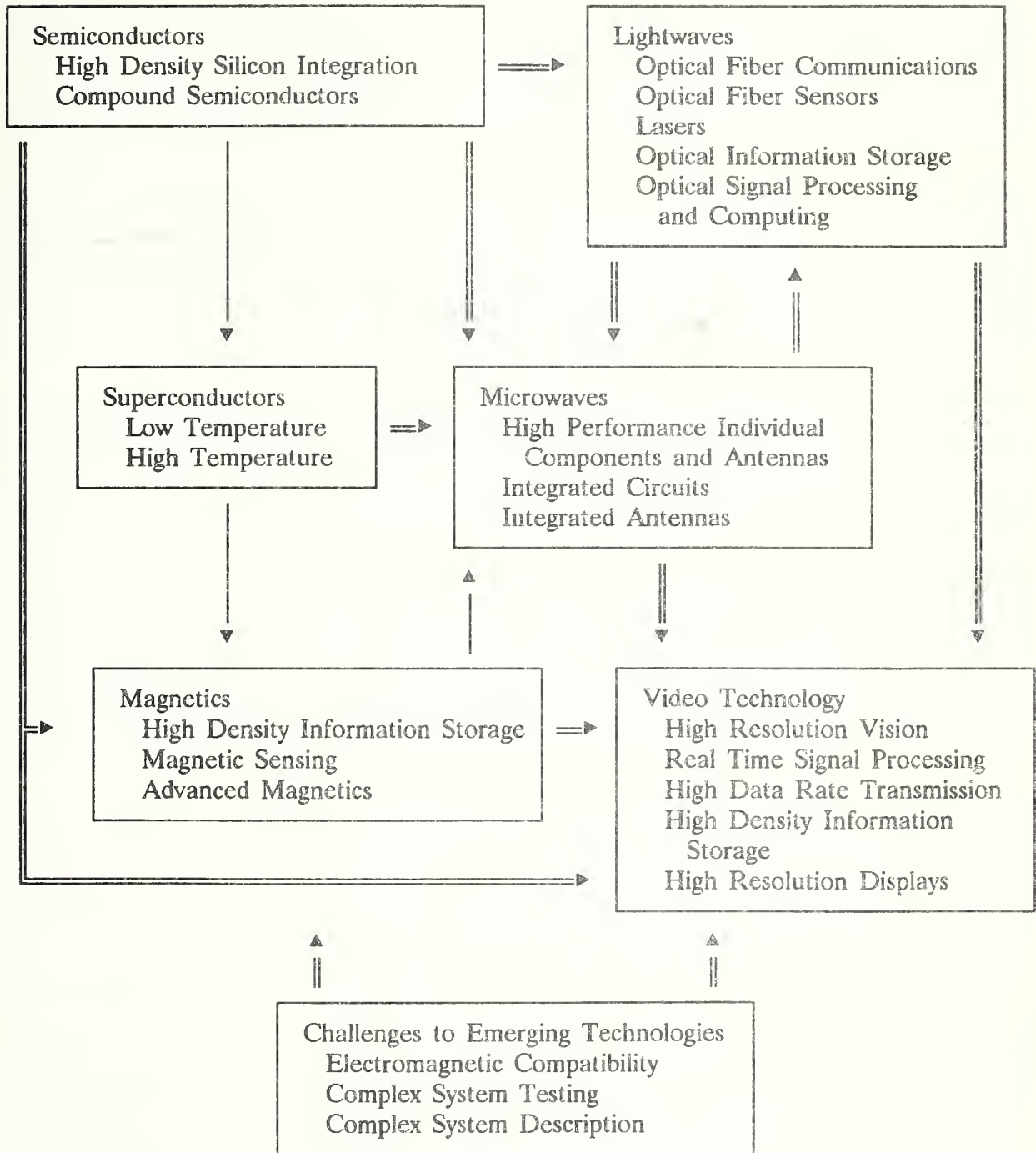
Video technology is the most integrative of the technologies. It depends on virtually all of the others except superconductors. For example, for information storage, video technology is highly dependent on magnetic and optical information storage. For transmission, video technology is highly dependent on microwave and lightwave technology. For displays, video technology is highly dependent on semiconductor technology, either for the generation of light or for the control of the displays. And so on.

The block labelled "challenges to emerging technologies" has not been connected to the other blocks in the diagram, for simplicity. But the success of all of the other technologies depends, to one degree or another, on resolution of the challenges listed there.

The far-term emerging technology of bioelectronics is not shown in the diagram. When bioelectronic technology is realized, it will complement semiconductors, and in some cases it will substitute for semiconductors.

These interdependencies are critically important. The U.S. cannot maintain competitiveness in the dependent fields without strength in the supporting fields.

Figure 1
Relationships Among Emerging Technologies in Electronics



Key

Technology A \Longrightarrow Technology B A supports B highly
 Technology A \longrightarrow Technology B A supports B moderately

Chapter 2
SEMICONDUCTORS
Phase 1 of New Program Plan

Summary

Electronics is a top-priority industry in every industrial and emerging nation in the world. Maintaining a successful competitive industrial position is unthinkable for any country without a strong electronics industry. Electronics is the largest manufacturing segment of the U.S. economy. The growth and impact of electronics has always depended on advances in the electron devices on which it is based.

Japan continues to be our major competitor. Japan and the U.S. produced the same amount of semiconductor devices in 1988, about 45 percent of the world market each. But over the past five years Japan has gained 10 percentage points of the world market at U.S. expense. Similarly, U.S. suppliers of semiconductor manufacturing equipment, while they still held a 57 percent share of the world market in 1988, have watched Japan's share rise 7 percentage points from 24 percent in 1983 to 31 percent in 1988.

These changes in the international competitive position are a measure of the success of different countries in coping with the extraordinary challenges posed by advancing semiconductor technology. That technology is evolving toward more complex semiconductor devices with ever smaller feature sizes, driven by desires for more powerful electronic systems and for reduced cost and size.

This evolution is increasing the demands on measurement technology. Better sensitivity and improved accuracy are needed. Absolute accuracy, not just repeatability, is becoming paramount for competitive manufacturing. Totally new measurement methods are required to cope with new materials and with automated manufacturing systems that depend on measurements made at high speeds. The measurement intensity of semiconductor manufacturing is increasing.

NIST's existing semiconductor measurements program primarily addresses measurement problems in the marketplace transfer of products between seller and buyer, and for technology transfer in the science and engineering community. Applications of this metrology to process control have been a valuable by-product of the program. But now the demands for in-process measurement and control are posing major challenges for U.S. industry. In fact, measurement problems afflict every aspect of the development and control of semiconductor manufacturing processes and equipment.

Also, many more fields of science and technology are being applied in semiconductor processes than before. The majority of these fall outside the scope of NIST's existing semiconductor measurements program. NIST has considerable additional expertise which has not been applied to these problems in the past because of limited resources. Application of a broader range of NIST's capabilities to the constantly growing array of severe measurement problems in semiconductor manufacturing would unquestionably benefit the industry. In response, NIST proposes a two-phase expansion of its program of measurement support.

Phase 1 of that expansion is the subject of this plan. It will provide measurement support for selected, critical problems of near-term concern in four areas:

- Process development and quality control
- Materials quality
- Device design
- Packaging design

In Phase 2, the program will expand to provide comprehensive measurement support for critical problems in all four areas, and with a longer term view.

Introduction

Electronics is a top-priority industry in every industrial and emerging nation in the world. Maintaining a successful competitive industrial position in the future is unthinkable for any country without a strong electronics industry. Electronics affects every aspect of life today. Electronic systems are integral parts of the nation's defense, communication systems, transportation, medical care, banking, manufacturing, etc. Electronics is the largest manufacturing segment of the U.S. economy, amounting to some \$248 billion in 1988 and growing at 11 percent annually.¹ It employs 2 million people. The growth and impact of electronics has always depended on advances in the electron devices on which it is based. "Over the past three decades, no single field of science or engineering has had a greater impact on the national productivity and quality of life in the United States than has semiconductor microelectronics."²

World Markets for Semiconductor Devices and Manufacturing Equipment

The world market for semiconductor devices is \$50 billion and for semiconductor manufacturing equipment is \$8 billion. U.S. production of semiconductor devices was \$22 billion in 1988 and is presently growing at 25 percent annually. U.S. production of semiconductor manufacturing equipment was \$4.6 billion in 1988.

U.S. International Competitive Position

Japan continues to be our major competitor. Japan and the U.S. produced the same amount of semiconductor devices in 1988, about 45 percent of the world market each. However, over the past five years Japan has gained 10 percentage points of the world market at U.S. expense. Similarly, U.S. suppliers of semiconductor manufacturing equipment, while they held a 57 percent share of the world market in 1988, have watched Japan's share rise 7 percentage points from 24 percent in 1983 to 31 percent in 1988.³

¹1989 Electronic Market Data Book, Electronic Industries Association, pp. iii, 3 (1989).

²Directions in Engineering Research, National Research Council (1987).

³Figures on the world and U.S. semiconductor manufacturing equipment markets come from the 1989 U.S. Industrial Outlook of the U.S. Department of Commerce, p. 30-9.

The competitive problems faced by the U.S. semiconductor-related industries are well known. Many significant studies, including those by National Research Council (NRC) (1986) and by the Defense Science Board (1987), have emphasized the seriousness of the U.S. deficiency in semiconductor manufacturing technologies. Japanese companies, while highly competitive with one another, are the beneficiaries of a variety of well-funded long-term programs of generic technological development initiated by their government.

Only recently has the U.S. responded by establishing SEMATECH, a consortium to rebuild U.S. excellence in semiconductor manufacturing. It will spend \$250 million per year for a minimum of five years and is funded by 14 member companies, the U.S. Government through the Department of Defense, and the State of Texas.

Relative to Japan, the U.S. still holds a slight technological edge in the several key areas of semiconductor manufacturing technology (ion implantation, thin film epitaxy, and film deposition and etching), but the Japanese have funded strong programs in these areas. The U.S. has already lost the lead in preparation of high quality semiconductor materials for making semiconductor devices and in major areas of existing semiconductor manufacturing technology (optical lithography and ceramic packages). The Japanese lead in new technologies for semiconductor manufacturing (microwave plasma processing, radiation sources for lithography, electron and ion microbeams, laser-assisted processing, compound semiconductor processing, and three-dimensional device structures). The U.S. is losing the lead in processing equipment. Further, the Japanese are outspending U.S. industry for capital improvements to their fabrication facilities, steadily pushing themselves ahead.

The Technological Challenge

The changes in the international competitive position are a measure of the success of different countries in coping with the extraordinary challenges posed by advancing semiconductor technology. That technology is evolving toward more complex semiconductor devices with ever smaller feature sizes. This evolution is driven by the desire for more powerful semiconductor products and for reduced cost and size, as shown in Table 1.

As this evolution takes place, the demands on supporting measurement technology increase. In particular, better sensitivity and improved accuracy are needed. Absolute accuracy, not just repeatability, is becoming paramount for competitive manufacturing. For example, according to Texas Instruments, absolute accuracy is necessary to enable processes to be transferred between plant locations, sometimes in different countries, and often using different makes of equipment. In addition, totally new measurement methods are required to cope with new materials and with highly automated systems that depend on measurements made at high speeds. The measurement intensity of semiconductor manufacturing is increasing; an estimated one quarter of the cost of semiconductor device manufacturing is now in measurement.

NIST's existing semiconductor measurements program largely addresses measurement problems in the marketplace transfer of products between seller and buyer, and for technology transfer in the science and engineering community. Applications of this metrology to process control

have been a valuable by-product of the program. But now the demands for in-process measurement and control are posing major challenges for U.S. industry.

Table 1
Evolution of the Technology

<u>Size of Device</u>	<u>Technology</u>	<u>Time Period</u>
centimeter	Vacuum Tube	1925-1960
millimeter	Transistors	1950-
micrometer	Integrated Circuits	today
submicrometer (0.1 micrometer)	Advanced Semiconductors - Silicon - Gallium Arsenide	tomorrow
nanometer (atomic size)	Atomic Manipulation - Quantum wells, wires, and dots	2000 (?)

Altogether, the semiconductor industry faces major measurement challenges in four key areas:

- Process development and quality control
- Materials quality
- Device design
- Packaging design

These areas also define the major elements of a new program of measurement support that NIST proposes to respond to the measurement challenges. Throughout this new program, NIST will focus on the domain of feature sizes extending down to 0.1 micrometer for integrated circuits. Grounds exist for believing that the physical limits of shrinking dimensions will be found near this level. Below this level, we may no longer be able to make microcircuits by present technological approaches.⁴

Why NIST?

NIST has special expertise in measurement science not matched by that in most, if any, companies. NIST discusses measurement problems with the industry while developing its plan of attack on an issue, and generally learns more about the questions than any one company

⁴NIST is planning other research programs to explore the possibilities of smaller feature sizes (nanometers) based on atom-by-atom assembly of circuits. There is much to be learned about working at the scale of individual atoms, such as the behavior of isolated atoms, how they cluster together into dots or lines (both of which have only recently become observable in some detail), and how they interact with surfaces. This is the domain of "Atomic Manipulation" in Table 1.

knows. NIST tries to solve the problems in a generic way not tied to a specific product development program, and to make its findings readily available to the industry at large through publications, direct contacts, and other appropriate means. NIST results usually start to flow to the industry soon after work begins, as interim developments appear. This flow can be accelerated to an individual company if it decides to place one of its employees at NIST as a Research Associate. NIST maintains a long-term research competence which is an invaluable resource for dealing with specific, new problems. NIST work thus stands on the best scientific and engineering foundation possible, and is carried to completion and widespread delivery in a way that is usually not feasible in an industrial environment where time pressures to deliver a product often override the wish to finish solving a measurement problem so that it is generically "right", and where the economic priorities of a single company seldom include contributions to the public good.

Many more fields of science and technology are being applied in semiconductor processes than were used before. The majority of these fall outside the skills now being applied by NIST in its existing semiconductor measurements program. NIST has considerable additional expertise which has not been applied to these problems in the past because funding has not been available for more work on semiconductor problems. There is no question that application of a broader range of NIST's capabilities to the constantly growing array of severe measurement problems in semiconductor manufacturing would benefit the industry. In this new program, NIST has identified a key subset of the major measurement problems that require attention. They are described below along with the contribution that NIST proposes to make to their resolution.

When appropriate, NIST carries its work to private voluntary standards organizations and actively helps these bodies use NIST work to develop new or revised standards. NIST is unique in having the national standards of measurement in house, allowing its measurements to be based on these standards with an accuracy not possible elsewhere. Finally, NIST is competitively neutral and objective. These qualities make NIST's results respected and easily accepted by all concerned.

NIST's New Program

The specific measurement challenges facing U.S. industry in the four key areas are described in the four sections below. Also described is the work that NIST would conduct in response. This work would be Phase 1 of a planned two-phase expansion of NIST's semiconductor program. Examples of work in Phase 2 are also given.

Each of the four key areas comprises one or more technical projects. Further details on those technical projects are provided later in this chapter in the section entitled "Detailed Description of Technical Projects" References to those projects are included below.

1. Measurements for Process Development and Quality Control

Semiconductor manufacturing is a complex multi-step process that simultaneously creates hundreds to thousands of copies of an integrated circuit on a semiconductor wafer that is five to eight inches in diameter. Each integrated circuit is composed of active semiconductor

devices (transistors) and passive devices (resistors and capacitors).⁵ During the manufacturing process, millions of these devices are constructed simultaneously in each integrated circuit. The devices are built up from multiple "layers" of materials. As the layers are constructed, the devices they form are interconnected by millions of conducting "lines" to form functioning integrated circuits. Hundreds of feet of such interconnections may be created within each of the integrated circuits on a wafer. The resulting integrated circuits are cut from the wafer. Each is mounted in a plastic or ceramic "package" and is wired to tens to hundreds of pins that extend outside the package. The pins of the package are later soldered to wired patterns embedded in printed circuit boards to form functioning products.

The process of making an integrated circuit requires up to 500 steps. Most of these steps cause irreversible changes, so a single processing error can make an entire wafer useless. Present measurement limitations make it difficult, if not impossible, to obtain high levels of quality control, especially as feature sizes are reduced and measurement problems intensify. Measurement is almost never possible during a processing step, even though this is the most desirable time because immediate correction may then be possible. Measurement is usually not possible even after every step, only some of them, so processing errors may not be caught early. The result is that additional, expensive processing steps are often applied to a wafer that has already become scrap.⁶

Plasmas: Process Development Measurements

Integrated circuits today are built using plasma-driven processes to deposit and remove surface films. The chemistry of these processes is not well known. The negative effects of the plasmas on the surfaces on which films are deposited are not understood, but those effects are becoming ever more significant.

In response NIST will develop measurement methods, reference materials data, and theoretical models on specific, initial selections of chemicals that will assist U.S. industry in developing improved plasma processing procedures and related plasma processing equipment. A wider range of chemicals and measurement techniques will be taken up in Phase 2. [For more information, see Project 5.]

Lines: Quality Control

As feature sizes drop below 1 micrometer, existing capability for measuring the sizes of those features begins to fail. At such small sizes, a clear view of what is being made requires electron microscopes, but accurate dimensional measurements with these instruments are not now possible. Soon it will be necessary to create even smaller patterns using x-rays from synchrotron sources.

⁵"Active" means capable of amplification or control of electric current.

⁶Gordon Moore, Chairman of Intel Corp., said at the 1988 International Reliability Physics Symposium that "poor quality in U.S.-made dynamic random access memories in the 1970's ... helped Japanese manufacturers win their foothold in world markets."

In response NIST will develop improved methods with supporting theoretical analyses and national physical standards for very high resolution optical measurements and even higher resolution electron microscope measurements with capability down to 0.1 micrometer. [For more information, see Project 4.]

Layers: Process Development Measurements and Quality Control

Semiconductor integrated circuits are built up from multiple layers deposited in succession. The complexity of these layers, and the degrees of control required to make them function successfully, are constantly increasing.

In response NIST will develop improved measurement methods for characterization of these layers, focusing on structure, defects, and electronic properties. NIST will apply new measurement techniques to provide additional information about the processes occurring at semiconductor surfaces, as a guide to improving fabrication processes. The scope of both of these activities will be expanded in Phase 2 of the plan.

NIST will provide reference data on semiconductor materials needed for accurate monitoring of fabrication steps. NIST reference data are carefully evaluated for accuracy and consistency. Data found in the technical literature may or may not meet these standards. NIST will provide Standard Reference Materials (SRMs) to support calibration of the analytical instruments that industry uses in process development. NIST SRMs provide a consistent calibration basis for the entire industry, unlike similar artifacts that may be developed by an individual company for its own use. [For more information, see Project 6.]

Finally, NIST will develop measurement methods for in-situ, nondestructive, and rapid characterization of layer quality to support quality control during manufacture. Contactless optical techniques will figure prominently in this effort. [For more information, see Project 1.]

Quality Control Analysis

Semiconductor manufacturing processes are so complicated that no easy way presently exists for determining what is making even an established process suddenly go wrong.

In response NIST will develop portable, generic artificial intelligence techniques to analyze data on the performance of process steps to determine the probable causes of deviations from normal performance. These techniques will bring the capabilities of experts (through "expert systems" analysis) to processing personnel who are not experts or whose expertise is limited. New work on the application of advanced statistical process control methods will be added during Phase 2. These NIST results will be freely available to U.S. industry, making it unnecessary for each company to duplicate the work independently and, quite likely, less completely. [For more information, see Project 3.]

2. Measurements of Materials Quality

Two principal classes of materials go into the making of integrated circuits: (1) the starting silicon and compound semiconductor materials on which integrated circuits or individual transistors are formed, and (2) the materials introduced during subsequent processing steps to form layers and interconnecting lines. NIST's existing program is already addressing the development of selected measurements to support control of the quality of the first class of materials above; this effort is increased in Phase 1 of this new program. For the second class of materials, this new program will be necessary to start addressing the problems.

For both classes of materials, greater purity is required as the feature sizes of integrated circuits are reduced. In some cases impurity levels less than 1 part in a trillion are required. The seriousness of the problem is reflected in reports from U.S. manufacturers that sophisticated integrated circuit manufacturing processes that work with materials supplied by Japan sometimes do not work with U.S. materials; yet U.S. measurement methods are unable to detect the differences between the two sets of materials.

Particles that were specks at larger feature sizes are boulders to smaller feature sizes, and cause catastrophic flaws in the chips. Particles arrive in both gases and process chemicals, and are generated by process equipment, material handling, and the people who work in the process area.

NIST will focus in Phase 1 on improving selected measurement methods for detecting (1) trace impurities in certain process chemicals and (2) moisture and particulates in process gases. Additional analytical problems will be addressed in Phase 2. These measurement methods can be used by industry for determining and controlling the quality of critical materials. [For more information, see Project 7 and Project 8.]

3. Measurements and Models for Device Design

As the size of semiconductor devices decreases, the solid-state effects of the boundaries of regions within the devices become significant. These effects were negligible at larger feature sizes. Computer models used in engineering design no longer correctly predict the behavior of the devices, leading to serious difficulties in creating new integrated circuits that work properly.

To assist U.S. industry in addressing these problems, NIST will develop measurement methods for determining key operating parameters of semiconductor devices and will provide theoretical models for relating device performance to key characteristics of the design and the materials from which the devices are made. NIST will also address the interaction of design with the performance of the ceramic and plastic packages in which the semiconductors are permanently mounted. [For more information, see Project 2.]

4. Measurements and Models for Packaging Design

As integrated circuits become more complex, so do the design requirements on their packages. More heat must be dissipated in smaller packages, more pins must be accommodated, and the sensitivity of integrated circuits to thermal stresses increases.

To assist U.S. industry in designing improved packages for emerging integrated circuits, NIST will develop measurement methods for performance-critical properties of packaging materials and will address thermal, chemical, mechanical, and electrical properties. NIST will also develop models that relate package properties to the processes used to form those packages so that improved packages can be developed by industry. [For more information, see Project 9.]

Impact

This new NIST program will strengthen U.S. competitiveness, improve productivity, and benefit manufacturers and buyers of electronic materials, manufacturing equipment, and devices by providing test methods, data, and computer models needed to diagnose problems that limit the performance of new and advanced electronic devices; develop monitoring methods for fabrication processes, manufacturing equipment, and production materials to improve reproducibility and product yields; and link critical materials and process properties to electronic device performance. Early NIST work has been shown to contribute significantly to U.S. industry's productivity⁷. Today the challenge to be met by NIST calls for substantially increased and broader ranging resources.

Detailed Description of Technical Projects In Phase 1 of New Program

The following sections describe in detail the nine technical projects that comprise Phase 1 of NIST's new program. They are the projects referenced above in the discussion of the four key areas of NIST's new program. Table 2 shows the priority order in which NIST would implement these projects.

Table 2
Order of Project Implementation

- Project 4: Submicrometer Dimensional Metrology
- Project 5: Plasma Etching and Deposition Process Measurements, Data, and Models
- Project 3: Metrology for Advanced Semiconductor Manufacturing
- Project 9: Metrology for Advanced Semiconductor Packaging
- Project 1: Metrology for Advanced Semiconductor Materials and Structures
- Project 8: Standards for Moisture and Particulates in Process Gases
- Project 2: Metrology for Advanced Semiconductor Devices
- Project 6: Surface Science for Semiconductor Manufacturing
- Project 7: Ultratrace Bulk Analysis for Advanced Semiconductor Devices

⁷Productivity Impacts of NBS Research and Development: A Case Study of the NBS Semiconductor Program, prepared by Charles River Associates for the U.S. Department of Commerce (June, 1981).

Project 1: Metrology for Advanced Semiconductor Materials and Structures

Programmatic description:

Semiconductor devices based upon advanced materials and structures are becoming increasingly complex. The establishment and use of quantitative techniques for materials and process characterization is crucial to improved yields and optimized performance. Two types of characterization techniques are important: (1) in-situ, nondestructive (contactless), and rapid measurements for process control, and (2) accurate diagnostic methods for quality control. The major goal of this project is the development of electrical and optical techniques of both of the above types for characterizing thin epitaxial layers and heterostructures to obtain their dimensions, composition, and electrical and optical properties and to evaluate their suitability in high-speed electronic and optoelectronic applications.

The project addresses measurement and process control problems in making very precisely deposited multilayer semiconductor structures composed of silicon, III-V, or II-VI materials used in advanced microcircuits for supercomputers, optical communications, and military applications. State-of-the-art GaAs/GaAlAs heterostructures of high quality can be prepared at NIST with a new molecular beam epitaxy facility. Silicon and other materials or structures will be obtained under joint industry-government projects.

Implementation plans:

Develop the capability to prepare and characterize epitaxial layers and structures of the highest possible quality with state-of-the-art optical and electrical measurement techniques. Employ precise optical probes for determining sticking coefficients, adsorption energies, and other information needed for detailed understanding of heteroepitaxial growth. Use highly perfect, well-characterized epilayers to generate reference data for the composition dependence of physical and electronic properties such as bandgap, effective masses, spin-orbit splitting, mobility, impurity state binding energies, heterojunction band offsets, lattice constant, phonon energies, etc. As appropriate, use these specimens as a basis for standard reference materials for properties such as composition, band gap, or lattice constant and for the uniformity of these properties. Gain a detailed understanding of the physical and electronic properties of these layers and structures to improve the yield and quality of advanced devices and to fabricate well-characterized Standard Reference Materials (SRMs).

Project 2: Metrology for Advanced Semiconductor Devices

Programmatic description:

The main goal of this project is to relate the operating characteristics of finished devices and circuits to the electrical, optical, and thermal properties of the materials from which they are made. This includes the metrology for determining operating performance, for transport properties such as mobility and carrier lifetimes, for verification of semiconductor physics used in models for devices and circuits, and for high resolution thermal analyses. The motivation is that submicrometer devices and circuits will require ultrahigh spatial resolution physical, electrical, and thermal analysis tools and ultra-high-speed instrumentation and signal

sources deliverable at the chip or packaged device/circuit level. The work will span devices and circuits for analog, digital, and integrated power (smart power, i.e., logic and power devices on the same chip) applications.

As the speed and reliability of devices and circuits are improved, computer assisted techniques, such as numerical simulations of how well devices and circuit perform, become more essential to success in the worldwide market place than they are today. Two- and three-dimensional effects are critical to the understanding of many reliability and yield problems. These problems include isolation associated with very densely packed devices and transient and steady state phenomena associated with radiation and electrically induced failure mechanisms. Addressing these challenges for U.S. industry requires careful evaluation of 1) the physics that is used in numerical simulations of devices and circuits made from both elemental and compound semiconductors; 2) the dependence of complex numerical algorithms on physical models; 3) the verification methods used for both physical models and numerical simulations; 4) the measurements of device and circuit performance; and 5) the interpretation of electrical, optical, and thermal measurements to give the many parameters that affect device, circuit, and package performance. These parameters for layered structures of insulators, elemental and compound semiconductors, and metals include band structure changes, band edge discontinuities, anisotropic mobilities, lifetimes, interface states and densities, thermal resistance, and heat removal rates. We also will be active with standards groups to 1) develop common formats for input and output files so that computer programs originated by one group are compatible with those originated by another group; 2) develop standards for ULSI packages; and 3) develop standards for specifying heat transfer properties and performance of power integrated circuits and packages.

Implementation plans:

Develop methods for measuring the critical physical, electrical, optical, and thermal properties of advanced semiconductor devices and circuits. This will include the fabrication of specialized electronic and optical structures, devices, and circuits on which such measurements will be made. Verify accurate physical models that numerically describe the performance of advanced microcircuits. Transfer NIST results to U.S. industry through direct collaboration and through standards setting organizations.

Project 3: Metrology for Advanced Semiconductor Manufacturing

Programmatic description:

This project builds on an existing one which has developed numerous test devices to measure the way in which individual process steps are executed. Apply artificial intelligence (computer techniques which include "expert systems", machine learning, and neural networks) to analyzing the data from these devices and to finding a probable cause for deviations from the norm. Demonstrate value of sound experimental design and statistical process control as an alternative to expensive, after-the-fact procurement testing. Coordinate industry-wide round-robin experiments to improve measurement capability on the factory floor.

Implementation plans:

An experimental machine learning system will be developed and exercised to demonstrate how such an approach can operate for analyzing selected portions of a VLSI process. The system will be implemented as an expert system. A test chip and measurement program will be customized to provide data associated with replicating submicrometer polysilicon features with optical lithography and reactive ion etching. A knowledge base will be obtained from test structure results and be compiled into a list of rules. Diagnostic tests will be developed to test and validate the accuracy of the rules. Methods will be devised to incorporate supplemental information from other sources within the manufacturing process into the knowledge base. An inference engine running on a small computer will be used to apply measurement data to the knowledge base. The intended output will be a diagnosis of failure modes in the feature replication process. The procedures developed will be applied to the characterization of a multilevel interconnect process, to electromigration under pulsed conditions, and to time-dependent dielectric breakdown (TDDB) of thin-film dielectrics. Initial efforts will be designed to establish quantitatively the present status of such characterizations, to identify sources of measurement ambiguity, identify any critically-needed research efforts, and to develop measurement standards in these areas.

Project 4: Submicrometer Dimensional Metrology

Programmatic description:

Accurate measurement of the critical dimensions of microstructures on semiconductor devices is essential to the control of the production process and the attainment of useful yields. The difficulty of making these measurements to the required accuracy is being compounded as planned generations of microcircuits will have feature sizes below 0.5 micrometer. It is essential to develop the metrological tools, both theoretical and experimental, to put these measurements on a solid foundation. For optical measurements, develop the required electromagnetic models for microstructures whose size is of the order of the wavelength of light and confirm these models by experiment. For scanning electron microscope (SEM) measurements, use Monte Carlo calculations to model the electron beam interaction with the sample, detector, and chamber and confirm the results by experiment with direct interferometry. Finally, in both these cases, the inverse problem must be solved (deducing the feature from the image rather than vice versa), suitable transfer standards must be developed, and the use of these standards in industry established.

Implementation plans:

Develop techniques for accurately measuring the critical dimensions of submicrometer features by optical and scanning electron microscopic techniques. Implement these techniques in the certification of new and improved feature-size standards and in recommended procedures for use in process verification by the semiconductor industry. The measurement techniques will include effects of the process procedure used to form the feature and the chemistry of the materials composing the feature; i.e., how the physical and chemical properties of the feature interact with the measuring electrical or optical beam.

Project 5: Plasma Etching and Deposition Process Measurements, Data, and Models

5.1 Advanced Plasma Etching for Semiconductor Manufacturing.

Plasma processing plays a central role in the manufacture of submicrometer semiconductor devices. Plasma etching is the primary technique used for selective material removal in the formation of the submicrometer features comprising these devices. Plasma deposition is gaining broader use given the advent of microwave plasma excitation methods. Although plasma reactors are commonly used in semiconductor manufacturing, plasma properties and ionization conditions, e.g., free electron kinetic energy distributions, ion and neutral species concentrations and energies, and the chemical kinetics of gas phase reactions, are not sufficiently well-developed to provide a basis for reliable design of new reactor technology alone. Therefore, the development of plasma etching reactors continues to require empirical correlations based on trial-and-error methods because the complex chemical and physical processes controlling their operation are not predictable. Additionally, process control strategies necessary to optimize process efficiency are not based on observation of the physical and chemical processes occurring in the reactor, but on measurements of reactor pressure, input power, and etchant gas flow rate and concentration. Process control strategies based on appropriate in-situ measurement or diagnostic techniques that probe the physical and chemical state of interactions between the wafer and gas phase species responsible for deposition and removal of wafer material will provide improved techniques for optimization of reactor operation.

To exploit fully the capabilities offered by plasma processing in semiconductor manufacturing, improved data bases, models and measurement methods are needed for a range of discharge conditions, excitation methods, etchant gases, and reactor types and geometries. Development of appropriate, well-characterized plasma discharge cells as standards provides an improved basis for evaluation in the industrial development of advanced plasma reactor technology. Validated data bases, models of plasma characteristics and properties and measurement techniques are vital components of such standards. Compilation, evaluation, and generation of fundamental chemical reaction rates, electron and ion transport parameters, and collision cross sections, and development of electrical, optical and mass spectrometric measurements and diagnostics for standard reference discharge cells form the fundamental basis of such reference standards development.

Currently radio frequency (RF) excitation of plasma reactors are used widely. Initial efforts will focus on the development of an RF discharge cell and will provide the basis for:

1. measurement of electron and ion transport parameters using a uniform field, drift tube-mass spectrometer system
2. calculation of electron-impact and ion collision and reaction rates using numerical solution of the Boltzmann transport equation and other techniques
3. computations to check the consistency between collision cross section data, transport data, and data from spectroscopic and ion measurements in rf reactor discharges

4. measurement of rf-discharge power dissipation and voltage and current phase and wave forms
5. measurement of ion mass and kinetic energy distributions for ions impinging on electrodes containing materials to be etched
6. utilization of optogalvanic spectroscopy (OGS) and electrical measurement methods to provide improved electrical measurement techniques for electron energy distribution
7. measurements of gas phase charged and neutral species concentrations using optical techniques, e.g., laser induced fluorescence and optical emission spectroscopy

Investigation of microwave plasma excitation methods will begin with the construction and operation of a discharge cell incorporating multi-polar microwave excitation. Extension of data bases and measurement techniques to this type of plasma reactor will be compared with the results from the RF discharge cell.

5.2 Diagnostics, Data, and Models for Plasma-enhanced and Laser-Enhanced Film Deposition and Removal Processes

Chemical vapor deposition (CVD), plasma deposition (PD), and plasma etching (PE) are important semiconductor device fabrication processes. However, the complex gas-phase reactions, which control product quality and reproducibility in these processes, are poorly understood. In practice, acceptable results are empirically obtained through optimization of the process parameters (e.g. temperature, pressure, concentrations) with little knowledge of the chemical principles which are involved. To fully exploit the capabilities of CVD and PE to improve device quality and provide for development of novel device structures, it is necessary to develop microscopic descriptions of reaction mechanisms in the gas phase and on the surface. This requires diagnostic measurements of gas phase reactants, intermediates, and products, as well as surface species and the epitaxial layer.

Complementary techniques used together can provide a wealth of information about gas phase processes. Mass spectrometric sampling is a generally applicable and, consequently, powerful method for monitoring stable end products and determining overall reaction kinetics. Laser-induced fluorescence is an extremely sensitive technique which is limited to a few species, but can measure the time-dependent, spatially-resolved concentrations of short-lived, reactive intermediates which control the gas phase chemistry. Excited state species in plasma- and laser-enhanced processes can be monitored by their spectroscopy via optical emission. The complexity of the gas phase chemistry requires that selective and accurate experimental measurements be used in conjunction with modeling of the reaction kinetics. The presence of the substrate in the gas/solid, two phase systems of CVD and PE processes cause temperature and concentration gradients in the reactors, which make mass and energy transport phenomena important, and, consequently, necessitate fully coupled chemical kinetic and fluid dynamic equations in the modeling.

Project 6: Surface Science for Semiconductor Manufacturing

6.1 Surface Structure Effects in Film Growth and Properties

Programmatic Description:

This project applies new techniques in surface science to the measurement and understanding of critical parameters in film growth and properties. The project will determine the role of surface atomic structure, atomic steps, and crystalline defects on the structural and electronic properties of deposited films. Similar investigations will be made of the properties of the "buried" interface after film deposition. The goal of the project is to develop fabrication and characterization methods so that films of the desired properties and quality can be produced efficiently and reliably.

Implementation Plans:

Surface measurement techniques such as x-ray photoelectron spectroscopy, Auger-electron spectroscopy, ion-scattering spectroscopy, and x-ray standing waves will be further developed and applied to determine film structure and properties. Photoelectron spectroscopy and x-ray standing wave experiments will be conducted with synchrotron radiation to exploit the sensitivity and spatial localizations possible.

The atomic structure at the metal-semiconductor interface plays a critical role in determining the characteristics of the Schottky barrier and of ballistic transport of electrons across the interface. The early stages of film growth will be investigated by the NIST-developed technique of electron forward scattering in x-ray photoelectron spectroscopy and Auger-electron spectroscopy which permits real-time observation of interdiffusion and clustering during thin film growth. Ion-scattering spectroscopy will determine the atomic structure of the film in the early stages of growth. The structural changes which occur in the buried metal-semiconductor interface during processing subsequent to growth will be investigated using synchrotron radiation at the Cornell facility using NIST-developed improvements in the technique of x-ray standing waves.

6.2 Mechanisms of Surface Processing

Programmatic Description:

This project applies new techniques in surface science to identify mechanisms of novel processing reactions at semiconductor surfaces such as etching, deposition, and lithography. It has recently been demonstrated that lasers and beams of particles such as ions and electrons can modify appreciably surface reactions and reaction rates. For example, silicon nitride can be produced at a much lower temperature on exposing a silicon surface to ammonia if concurrent electron bombardment is applied; the lower processing temperature is critical in not modifying dopant concentrations formed at earlier processing steps. Advances in surface processing are required in developing new devices with submicrometer dimensions due to the drastic concentration gradients, interfacial phenomena, material compositions far from equilibrium, and sensitivity to defects.

Implementation Plans:

Novel laser probes will be developed and applied to monitor non-thermal surface chemical reactions stimulated by laser, electron, or ion beams.

Chemical reactions driven by non-thermal stimuli will be identified and optimized. In situ optical probes of surface species during interface processing (etching, CVD, annealing) will be developed. Optical techniques capable of following the reaction rate and chemical intermediates involved in processing environments will be utilized. Laser, electron, and ion beams will be used to selectively generate reactive species. The influence of beam energy on reaction rate, reaction cross section, and reaction products will be addressed. Techniques will be developed to quantify the efficacy of existing surface modification processes as well as examining the potential for new beam-initiated modification processes. Experimental techniques will include laser ablation, laser-generated radical beams, surface vibrational spectroscopy, time-resolved optical probes, electron- beam-induced reactions, and reactions induced by energetic ion beams. The project will combine state of the art laser diagnostics with controlled surface characterization and theoretical efforts to establish the fundamental events in non-thermal device fabrication.

6.3 Standard Reference Data and Materials

Programmatic Description:

This project provides two important delivery mechanisms for this initiative. Reference data on semiconductor material properties are needed for accurate monitoring of device fabrication steps. Reference materials are needed for calibrations in industrial laboratories of complex analytical systems.

Implementation Plans:

Obtain data for the critical parameters required for surface and interface analyses of semiconductor materials and devices. Kinetic and thermodynamic data are required to describe reactions in plasmas and on surfaces exposed to them. Measure, evaluate, and compile these data into computer-readable databases. Establish priorities and develop plans for new Standard Reference Materials (SRMs) for calibrating instruments for surface and interface characterization of electronic materials. SRMs of the following types are needed: ion-implanted semiconductor materials with known concentrations and depth distributions, multilayer metal thin-film materials of known thickness, superlattice materials, organic materials, and multicomponent materials for calibration of instrument sensitivities.

(a) Standard Reference Data

This project will provide critical data required for surface and interface analyses of semiconductor materials and thin-film devices. Data are particularly needed for the following parameters: electron attenuation lengths; matrix effects on elemental sensitivity factors; electron backscattering correction factors; the effects of specimen crystallinity on measured intensities for surface-characterization spectroscopies; and ion sputtering rates. Data for these

and other important parameters will be measured, evaluated and compiled in the form of computer-readable databases for efficient and convenient distribution. Improved algorithms will be developed for analysis of spectroscopic measurements. These algorithms together with the new data bases will be incorporated into new expert systems that will be designed to improve the accuracy and efficiency of surface measurements. Kinetic and thermodynamic data will also be measured and compiled to describe reactions in plasmas and on surfaces exposed to them.

(b) Standard Reference Materials

Standard Reference Materials (SRMs) will be fabricated and characterized for the calibration of instruments used for surface and interface characterization of electronic materials. SRMs of the following types are needed: ion-implanted semiconductor materials with known concentrations and depth distributions; oxide thin-film materials of known thickness; multilayer metal thin-film materials of known thickness; superlattice materials; organic materials; and microroughness standards for calibration of surface roughness measurements following processing by energetic beams. Methods will be developed to produce some materials in highly ordered state and others that are highly disordered.

Project 7: Ultratrace Bulk Analysis for Advanced Semiconductor Devices

With the accelerating trends toward higher purity materials and toward smaller devices, the absolute amounts of impurities that must be determined in semiconductors are beyond the current state-of-the-art practice. The broad experience of elemental analysis applied to ultratrace measurement in materials characterization can be applied to the special problems of advanced semiconductors. The existing techniques of Isotope Dilution Mass Spectrometry (IDMS), Inductively-Coupled Plasma with both Atomic Emission Spectroscopy and Mass Spectroscopy (ICP-AES and ICP-MS), Ion Chromatography (IC), and Neutron Activation Analysis (NAA) provide an unmatched combination of analytical tools for addressing this challenge. The longstanding expertise in clean room chemistry and ultra-pure reagents ensure an effort that will be productive from the first day. The demonstrated capabilities in elemental analysis from ppb to below ppt in favorable cases can be further developed for the unique semiconductor requirements. The production of SRMs characterized for elemental ultratrace composition will be a natural result of this effort.

Project 8: Standards for Moisture and Particulates in Process Gases

Moisture and particulates are the most important factors that contribute to device rejection and reduced productivity. Current humidity measurement techniques are limited to concentration levels above 1 ppm. New processes used for fabrication of submicrometer scale devices require measurements of humidity levels below 1 ppm. Measurements at such low concentrations would require development of new techniques utilizing optical methods. One such technique, which will be explored as part of this work, involves the use of a tunable diode laser for multipass infrared absorption measurements. This technique should provide reliable humidity measurements down to approximately the 10 ppb level. The system accuracy and precision would be evaluated using a low dew point humidity generator currently being constructed at NIST.

Particulate contamination is another critical source of process inefficiency in microelectronics fabrication. This situation is expected to be further aggravated as the dimensions of microstructures are reduced below a micrometer. Submicrometer particles, either introduced in the input gas stream or generated in some part of the process (such as by homogeneous gas-phase nucleation of SiO₂ particles), will represent a major source of device contamination and have to be measured and controlled at each step of the process. These techniques are to be utilized for on-line measurements and real-time control of fabrication processes. Stringent specifications and a priori measurements of these parameters are not sufficient to reduce the rejection rate of semiconductor devices, since moisture and particulates could be entrained in the transfer lines and introduced into the reactor. Therefore, on-line measurements in the reaction chamber are necessary to ensure high product quality.

Project 9: Metrology for Advanced Semiconductor Packaging

The \$2.0 billion U.S. market for microelectronics packaging is currently dominated by foreign suppliers. Microelectronic packaging is a core technology for electronics, computer, TV and many other high tech industries. The technical trend is towards faster, larger, and more compacted integrated circuits with finer and finer linewidths. The electrical circuit linewidths on the chips are projected to decrease from the current 0.5-1.0 micrometers to less than 0.1 micrometers by the year 2000; simultaneously, linewidths in the packaging are projected to decrease from the current 50-100 micrometers to 10-25 micrometers. With the compaction of such dense electrical circuits, materials with high thermal diffusivity (ability to dissipate heat quickly) and low dielectric constants (ability to store electrical charge) become crucial technology barriers. In order to accommodate such dense packing, thin films of dissimilar materials are used. The properties across the interface, variations, defects, homogeneity influence performance significantly. The development of the next generation of new materials and the ability to intelligently design such complex systems taking into account microscale materials property variation ranges is a deciding factor for competitiveness.

One of the crucial needs is accurate, precise measurement techniques to measure materials properties and performance at such complex microscale. Critical data at materials interfaces are difficult to obtain yet they are required for intelligent design and modeling. The main objective of this effort therefore is to develop measurement methods for determining the performance-critical properties of the materials in microelectronics packaging. The development of these measurements technologies is at the core of the NIST mission. Industry has come to rely on NIST for development of such measurement technologies. An auxiliary objective is to develop experimentally validated models of the processing-structure-properties-performance relationships in order to capture the knowledge gained from the measurements in design-usable forms and to guide the course of the project by identifying the most important properties to be measured.

Measurement techniques available to NIST will be upgraded and in a few cases new techniques will be developed to measure the performance-critical properties. These properties include microstructure (size, shape, anisotropies), composition (elemental and phase), state of strain, strength, adhesion, impedance, dielectric constant, and thermal diffusivity. The techniques to be used for measuring the microstructures will include optical and electron microscopy (SEM, TEM, and EBSP), x-ray laminography and acoustic microscopy. For

composition, techniques such as electron probe microanalysis, magic angle spinning NMR, micro-Raman spectroscopy, ESCA, XPS, RBS, and Auger analysis will be used. States of strain will be determined by x-ray, micro-Raman, Ruby fluorescence, and microstrain gauging methods. Adhesion will be determined by microtraction, microindentation, and pull-off methods. Strength will be determined by microindentation and micromechanical methods and procedures to be developed. Impedance will be measured by direct contact. Dielectric constant will be measured by direct contact and microwave, infrared and optical absorption. Thermal diffusivity will be measured by mirage and thermal wave imaging and forced Rayleigh scattering.

Specimens produced by NIST and industry under well controlled and monitored conditions will be analyzed by the appropriate techniques. Types of specimens will include metal conductor on ceramic substrate (metal-ceramic), metal conductor on polymeric substrate (metal-polymer), and solder on metal (metal-metal). Examples of ceramics to be studied are Al_2O_3 , AlN, and SiC. Metal conductors include glass-filled Ag, Au, Pd, Pt, W, Mo and Cu. Polymers of interest include glass-filled epoxies and polyimides. Solders of the varieties most commonly used in microelectronics packaging will be studied.

Specimens will undergo simulated service cycles in which temperature and humidity, the main parameters affecting the in-service reliability of microelectronic packages, are systematically varied. Using the measurement techniques developed above, the properties of the specimens will be measured as functions of time of exposure and correlations between the properties, the processing parameters and service conditions will be sought.

The knowledge gained in the experiments will be captured in the form of finite element models for predicting the structures and properties of the specimens as functions of the processing parameters and to predict the performance and durability of the specimens implied by the as-produced structure and properties. The results of the modeling will be used in an iterative fashion to identify the most important properties to be measured in the experiments above.

Chapter 3
SUPERCONDUCTORS
Phase 1 of New Program Plan

Summary

The technology of low temperature superconductivity (LTS) has been under serious development since the discoveries of the high field superconductors in the late 1950s and the Josephson effect in the early 1960s. It has already produced major engineering successes, among them many large magnets for bubble chambers and controlled fusion experiments, the Tevatron at the Fermi Laboratory, the experimental magnetically levitated train developed by the Japan National Railways, Magnetic Resonance Imaging, the very fast 4-bit microprocessors developed by Fujitsu and Hitachi, and the Josephson junction array voltage measuring system developed by CEEE.

These and several other very promising applications of superconductivity have all been studied and developed with low temperature superconductors. The discovery of high temperature superconductors (HTS) has stimulated much new exploration. All these ideas are receiving fresh attention, and new ones are being added. The future of this field is difficult to predict but holds great promise.

Market Projections and Prospects

The growth of the superconductor market forecast by World Business Publications predicts a total of \$1.3 billion by 2003. This represents the market for both low temperature superconductors, which account for all the present market, and high temperature superconductors, which are expected to dominate the market in the later years. Note that already in 1988 there was a market of \$172 million for low temperature superconductor projects.

Japanese forecasters take a generally more optimistic view than those in the U.S. The Nomura Research Institute forecasts a total world market of \$43 billion in 2000 and \$123 billion in 2010. This view is encouraged by the higher level of industrial research on superconductivity in Japan than in the U.S.

The main barrier to the creation of a large market for LTS is that it requires liquid helium refrigeration, which is expensive and widely distrusted, largely because it has never been developed on a commercial scale. High temperature superconductivity (HTS) promises to eliminate this barrier by substituting at least liquid nitrogen refrigeration, which is cheap and well established on a commercial scale. This would then reduce the overall cost of the technology if other costs (such as that of the conductors themselves) do not turn out to be greater.

The basic components of a practical HTS technology do not exist yet, but steady progress is being made in their development. Critical current densities over 10^6 amperes per square centimeter have been reported in thin films, and over 10^4 amperes per square centimeter in bulk material in low magnetic fields, falling to much lower values as the magnetic field is increased. Single layer microcircuits can be fabricated by photolithography and successful

insulating crossovers have been reported. A large effort has not yet produced a controllable technique to fabricate Josephson junctions, but the Josephson effect has been observed in a variety of HTS structures.

All the remaining problems may be overcome by clever ideas, just as similarly difficult problems in LTS were overcome. But they create great uncertainty in the future of HTS technology, especially in the time scale for practical, commercial development. A prudent plan is to continue the development of LTS technology in parallel with early efforts in HTS technology until the latter demonstrates clear superiority in each application. CEEE has a strong effort in LTS in the base program.

The NIST Superconductivity Program

The NIST Superconductivity Program is a collaborative effort among many parts of NIST. The program brings a very wide variety of skills and measurement facilities to bear on the difficult problems posed by superconductivity. The description below addresses the overall NIST program while highlighting the work done by CEEE.

1. Measurement Methods for Electrical and Magnetic Characteristics: The engineering characteristics of superconductors present unique measurement problems that have been the subject of research at NIST (in CEEE) for over two decades. These include the measurement of critical current and its variation with magnetic field, temperature, mechanical strain and other test conditions; the measurement of AC loss and other magnetic characteristics; the determination of the limits of stability; and the measurement of basic superconductor characteristics such as the energy gap, the isotope effect, etc. These measurement problems are of equal importance in ceramic and metal superconductors. Standards activities include the development of ASTM standards, a Standard Reference material for critical current measurements, and international coordination through the VAMAS organization (Versailles Agreement on Advanced Materials and Standards).

2. Composition and Structural Analysis: Systematic development of the ceramic high temperature superconductors must be guided by reliable determination of chemical composition and physical structure of test specimens. NIST has established a wide range of test facilities for this purpose. These include neutron scattering (both elastic and inelastic); x-ray diffraction (including a catalog of diffraction patterns); photoemission spectroscopy; micro-Raman spectroscopy; electron and ion microprobe analysis; neutron activation analysis; isotope dilution mass spectrometry; and ultrasonics. Applying all these techniques to one specimen enables a comprehensive analysis of structure and composition to be made at a wide range of scales.

3. Data for Design and Control of Fabrication Processes: The design of fabrication processes for ceramics depends upon information relating process variables to product materials. Research to establish such data for the high temperature superconductors is in progress in NIST. This includes the establishment of phase equilibrium diagrams; devising and testing process conditions to promote grain orientation; preparation of starting materials in optimum form; and the establishment of processes to fabricate thin films of high quality.

4. Development of Superconducting Devices for Measurement Systems: There has been a program in superconducting electronics at NIST (in CEEE) for over two decades, with the objective of developing the next generation of techniques, instrumentation and physical standards for a variety of electrical and magnetic measurements. There is a fabrication facility for superconducting microcircuits that has produced SQUID magnetic detectors, an A/D converter, a fast counter, millimeter wave mixers, and a voltage measurement system that incorporates the basic national standard. All these are based on thin films of low temperature superconductors and Josephson junctions. Present work includes further development of a power standard for infrared and microwave radiation based on a kinetic inductance bolometer. Research to extend the fabrication of microcircuits to high temperature superconductors is in progress. This includes the establishment of processes to fabricate high quality thin films and perform lithography. The greatest challenge is to fabricate reproducible Josephson junctions, and some progress has been made in applying the proximity effect to this problem.

Proposed New CEEE Program

The CEEE superconductivity program has always worked in collaboration with other organizations. Over half of the funding of the LTS program is from other agencies. The HTS program continues this practice. For example, a major project to develop controllable fabrication methods for HTS Josephson junctions is funded by DARPA. The development of low resistance contacts is a joint project with Westinghouse, the development of photolithography of HTS films is a joint project with AT&T, and there are many other examples. CEEE encourages visiting researchers and is ready to collaborate with other organizations developing materials and needing help with diagnostics. CEEE contributes to three of the four projects addressed by the NIST Superconductivity Program. Those contributions are summarized below and represent a first phase of the CEEE component of the new program.

1. Measurement Methods for Electrical and Magnetic Characteristics: It is now widely recognized that variations in measurement methods and definitions (particularly of critical current) can cause differences of over a factor 10 in reported results, which is making nonsense of the technical literature. CEEE is already taking a leadership role in standards activities to solve this problem, but present resources are too small to be effective. Extra resources are needed to mount a nation-wide effort in a timely manner.

3. Data for Design and Control of Fabrication Processes: The major unsolved problem preventing early engineering applications of HTS is the small current-carrying capacity of these materials in high magnetic fields. This is caused by weak flux pinning. CEEE has world experts in measuring and optimizing flux pinning, gained from two decades of experience in LTS. An expanded effort to apply these resources to the problem will be very effective.

4. Development of Superconducting Electronic Devices for Measurement Systems: World leadership in superconducting digital electronics resides in Japan, but CEEE has two decades of experience in LTS electronics. Expansion of this program will provide a nucleus for an effort in the U.S. to move ahead in HTS electronics.

Introduction

The technology of low temperature superconductivity (LTS) has been under serious development since the discoveries of the high field superconductors in the late 1950s and the Josephson effect in the early 1960s. It has already produced major engineering successes, among them many large magnets for bubble chambers and controlled fusion experiments, the Tevatron at the Fermi Laboratory, the experimental magnetically levitated train developed by the Japan National Railways, Magnetic Resonance Imaging, the very fast 4-bit microprocessors developed by Fujitsu and Hitachi, and the Josephson junction array voltage measuring system developed by CEEE.

The major commercial success to date is Magnetic Resonance Imaging (MRI), which enjoys a worldwide market of approximately \$1 billion for complete systems.¹ MRI is a medical diagnostic technique that requires a strong, highly uniform, and controllable magnetic field in a volume sufficient to accommodate the body of the subject. This and other medical applications of superconductivity have great market potential. Among the most promising is magnetoencephalography, or mapping of the electric current distribution in the brain using an array of SQUID magnetometers. This technique is at present in the medical research phase, and is being shown to be capable of providing diagnostic information on the brain that is not accessible by any other means.

The development of high energy particle accelerators has led to the construction of many large and successful superconducting bending and focusing magnets, and to the solution of major engineering problems associated with the stability of large superconducting systems. A fine example is the Tevatron, at the Fermi Laboratory near Chicago, which features a ring of superconducting magnets 5 km in circumference. It works as designed. The Superconducting Super Collider (SSC) will be a similar machine but ten times bigger. Liquid hydrogen bubble chambers are used as detectors in high energy physics experiments. They also require high magnetic fields in large volumes, to identify charged particles and measure momentum. Perhaps the most significant potential application of large superconducting magnets is to controlled thermonuclear fusion. Some very large magnets have already been constructed for experiments in magnetic confinement, and it is generally recognized that performance that can be achieved only by a superconducting magnet would be essential to the success of a magnetically confined fusion reactor.

In the electric power industry, superconducting magnetic energy storage (SMES) is seen as the most immediate application of superconductivity. Energy storage has great significance in the economics of electric power systems, which must cope with a demand that has large periodic variations. The supreme advantage of SMES is that it does not require energy conversion (except for the conversion of electricity from AC to DC), and can therefore be very efficient. There have been many studies of power transmission and generation with superconductors. A superconducting transmission line would indeed be capable of costing less energy than a conventional one, but the economic advantage would be largely offset by the need to lay it underground, instead of overhead which is cheaper. The main advantage of

¹Diagnostic Imaging (August, 1989).

superconductors for generation is that superconducting windings would enable the machines to be made about half size for the same power rating. This would raise the limit on large machines, which is set by the maximum size that can be transported from factory to power station. This limit is an important factor in the economics of power generation.

The most exciting prospect in transportation is the magnetically levitated train (MAGLEV). An experimental train developed by the Japan National Railways is capable of travelling at 500 km per hour, levitated by superconducting magnets (carried on board) above a special aluminum track. The drive is by linear induction motor. This train has carried passengers, and development is continuing with the objective of placing MAGLEV trains in commercial service.

Ship propulsion is also a very promising field. A compact electric drive that eliminates the constraints of accommodating a straight propeller shaft would permit the design of a more compact, efficient hull for a given payload. The benefit would then be compounded by needing to carry less fuel. The U.S. Navy has a program to develop a superconducting ship drive that has already produced a small prototype version for sea trials. Another possibility that is under investigation in Japan is to eliminate the propeller and use instead the magnetohydrodynamic (MHD) effect to impel seawater directly.

In electronics, there is a modest commercial market of \$5-10 million for magnetic measuring instruments based on the superconducting quantum interference device (SQUID). The market is mostly for scientific instrumentation in applications where great sensitivity is required. One of these is magnetic anomaly detection (MAD), a military surveillance technique. Another commercial instrument is a sampling oscilloscope with 5-ps resolution. This out-performs all other electrical sampling systems by almost an order of magnitude, but the market for it appears to be small at present.

Several successful measuring devices under development at NIST are not yet on the market. These include a 30-bit binary counter that is capable of counting at rates up to 100 GHz, an analog-to-digital converter that can operate at rates in the GHz range, and a voltage standard that is part of an automated voltage measuring system that can refer voltage measurements in the range up to 12 volts directly to the international definition of the volt, with uncertainty of a few tens of parts per billion. The microcircuit at the heart of this system contains 19,000 Josephson junctions (the active elements of superconducting electronics). This is among the most complex superconducting microcircuits that have been achieved so far.

The application of superconducting electronics of the greatest commercial potential is to computers. The speed of computers will be limited ultimately by the delay in communication among the components. Thus achieving the highest possible computing speed will require packing a very large number of components very close together. This will most probably be limited by the need to dissipate the heat they generate, so one can define a figure of merit that depends on a combination of short switching speed and small energy dissipation on switching. By this measure superconducting devices are superior to all others, partly by virtue of operating at low temperature. Also, superconducting transmission lines may contribute to reducing communication delays. An ambitious project at IBM to develop a commercial superconducting computer was dropped because it fell behind the marketing schedule. Since

then the work has continued in Japan, and recently both Fujitsu and Hitachi have announced 4-bit microprocessors with clock rates over 1 GHz. These are experimental devices, but the promise is great.

Another fruitful field for the application of superconductivity is radiation detection. Compact but efficient antennas can be made with superconductors that have ohmic resistance that is small compared to the radiation resistance. These are simple, one-layer devices that may provide an early field of application for high temperature superconductors. Millimeter wave mixers with very low noise and good conversion efficiency are under development by a joint project between the University of California at Berkeley and NIST. The Kinetic Inductance Bolometer is also under development at NIST, both for a power standard and for a radiation detector. It is unique among radiation detectors in that it generates no thermal noise internally. Other ingenious devices are under development for radiation detection in all parts of the spectrum and for signal processing.

These very promising applications of superconductivity have all been studied and developed with low temperature superconductors. The discovery of high temperature superconductors (HTS) has stimulated much new exploration. All these ideas are receiving fresh attention, and new ones are being added. The future of this field is difficult to predict but holds great promise.

Market Projections and Prospects

The growth of the superconductor market forecast by World Business Publications is shown in Table 1. This represents the total market for both low temperature superconductors (which account for all the present market) and high temperature superconductors, which are expected to dominate the market in the later years. Note that already in 1988 there was a market of \$172 million for low temperature superconductor products.

Japanese forecasters take a generally more optimistic view than those in the U.S. The Nomura Research Institute forecasts a total world market of \$43 billion in 2000 and \$123 billion in 2010. This view is encouraged by the higher level of industrial research on superconductivity in Japan than in the U.S.

The main barrier to the creation of a large market for LTS is that it requires liquid helium refrigeration, which is expensive and widely distrusted, largely because it has never been developed on a commercial scale. High temperature superconductivity (HTS) promises to eliminate this barrier by substituting at least liquid nitrogen refrigeration, which is cheap and well established on a commercial scale. This would then reduce the overall cost of the technology if other costs (such as those of the conductors themselves) do not turn out to be greater.

The basic components of a practical HTS technology do not exist yet, but steady progress is being made in their development. Critical current densities over 10^6 amperes per square centimeter have been reported in thin films, and over 10^4 amperes per square centimeter in bulk material in low magnetic field. Single layer microcircuits can be fabricated by photolithography and successful insulating crossovers have been reported. A large effort has

not yet produced a controllable technique to fabricate Josephson junctions, but the Josephson effect has been observed in a variety of HTS structures.

Table 1
Estimated Future Markets for Oxide and Niobium
 Based Superconductors by Area of Application²

(millions of dollars)

<u>Sector</u>	<u>1988</u>	<u>1993</u>	<u>1998</u>	<u>2003</u>
Electronics (approx.)	5-10	50	200	800
Electric Power	2	7	20	45
Medical MRI Magnets	130	140	165	180
Transport Systems	-	-	5	25
Magnetic Separation	3	20	60	175
High Energy Physics	30	350 ³	80	100
Other Industrial	- ⁴	5	10	20
Total (approx.)	172	572	540	1345

Basic theoretical questions have been raised about the feasibility of solving the remaining problems in the development of a working HTS technology. Sustaining a high critical current density in a high magnetic field requires flux pinning, which is weakened at high temperature by thermally activated flux creep and the melting of the fluxoid lattice. It will be very difficult to fabricate Josephson junctions in HTS materials by the methods that have been successful with LTS. The chemistry of the oxide ceramics eliminates many candidate materials for their insulating barriers, and the very short coherence length compounds the problem. The attractive feature of LTS for computers is that operating at low temperature enables low switching barriers (with the attendant low switching energy) to be used without interference by thermally induced random switching, thus there is some question if a superconducting computer operating in liquid nitrogen would have any advantage over semiconductor technology.

All these problems may be overcome by clever ideas, just as similarly difficult problems in LTS were overcome. But they create great uncertainty in the future of HTS technology, especially in the time scale for practical, commercial development. A prudent plan is to continue the development of LTS technology in parallel with early efforts in HTS technology until the latter demonstrates clear superiority in each application.

²World Business Publications, as published in Superconductor Week (February 27, 1989).

³Includes niobium based superconducting magnets for the Superconducting Super Collider.

⁴Estimated at less than \$1 million.

Summary of the CEEE Program

Objectives

1. Provide a basis of test methods, measurements, and standards to support the development of practical superconductors (both LTS and HTS).
2. Develop applications of superconducting electronics to physical measurements and standards, and assist other organizations to adapt them to their needs.
3. Share the benefits of the unique CEEE expertise and experience in superconducting electronics with other efforts in the U.S. to develop a practical technology.

The superconductivity program in CEEE has been serving the development of LTS technology for over two decades.

The conditions affecting the switching of superconductors to the resistive state were determined and a reliable technique to measure moderate (less than 600 amperes) critical current was established as an ASTM standard, backed up by a standard reference material and an extensive published discussion of factors affecting the result. Before this work discrepancies of 40% between measurements made by different laboratories were usual. Agreement within 10% is now the norm. The degradation of critical current by elastic strain was discovered and investigated. In some superconductors, 1% strain can degrade the critical current in high magnetic field by over 50%. A strain scaling law was established. Consistent measurement methods for AC loss were established, and the causes of instability of the current-carrying behavior of superconductors were determined.

Techniques were developed to measure the energy gaps of bulk specimens of superconductors using mechanical break junctions and squeezable electron tunnel (SET) junctions. Systems were developed to measure the magnetic properties of superconductors.

In electronics, there was extensive early work on magnetic measurements, including pioneering studies of magnetoencephalography, and also on DC and RF electrical measurements, noise thermometry, and sub-millimeter wave mixing. A fabrication facility for superconducting microcircuits was established and used to produce waveform samplers, analog to digital converters, fast counters (all performing beyond the previous state of the art), and magnetic detectors with noise level near the fundamental limit set by quantum fluctuations. A major project produced first a 1-volt standard now used as the national standard for voltage by the U.S. and by other nations, and then an automated voltage measurement system based on an array of 19,000 Josephson junctions, capable of a variety of voltage measurement functions with direct reference to the international definition of the volt at very high accuracy. The next highly promising project is a kinetic inductance bolometer that is being developed as a power standard for both the infrared and the microwave ranges of the spectrum.

After the discovery of HTS, it was found that many experimental techniques developed for LTS could be adapted to serve very well, and many of the measurement problems were similar but often in exaggerated form. The problems of defining and measuring critical

current are a good example. Electrical contacts to the ceramic superconductors were a severe early problem that was largely solved at NIST (in a collaborative project with Westinghouse) for conductors of medium size, with an improvement of eight orders of magnitude in contact resistivity compared with the previous art. Well calibrated and carefully analyzed magnetic measurements were applied to the study of intergranular coupling in HTS. Break junctions and SET junctions produced some of the best available measurements of the energy gaps of the new ceramic superconductors.

In electronics, the first achievement was an RF-biased SQUID based on a break junction. This operated in liquid nitrogen with a sensitivity that was outstanding at the time and has been surpassed only by a modest margin. The fabrication of thin HTS films with good superconducting characteristics was established. Photolithography was found to be successful when applied before the final heat treatment to adjust the oxygen stoichiometry of the films. Working HTS infrared bolometers have been fabricated. Preliminary experiments have been made to take advantage of the superconducting proximity effect, to fabricate Josephson junctions in which the more tractable qualities of metals can be used while superconductivity is sustained at high temperature by contact with a ceramic superconductor.

General Strategy of the CEEE Program

There are major national programs in LTS that will continue to be supported. In fact, in FY 1989 the total Federal funding of LTS (\$129 million) is slightly greater than that of HTS (\$128 million). In CEEE the major projects in LTS are to establish consistent measurement of critical current of very large conductors and to study AC loss, to take the lead role in establishing international consensus on measurement methods through the Versailles Agreement on Advanced Materials and Standards (VAMAS) organization, to support with measurement research the development of the superconducting super collider (SSC) and fusion energy devices, to develop the full potential of the kinetic inductance bolometer and an analog to digital converter based on the fast counter, and to establish the existence of phenomena that have been predicted theoretically to occur in very small Josephson junctions and that may have technical and fundamental-standards potential.

The major unsolved problem in bulk HTS material is to sustain a high critical current density in high magnetic field, which will depend upon developing a material with stronger flux pinning. The CEEE program will include a major effort in flux pinning engineering in bulk material, composites, thick films and thin films. Alternate methods of measuring critical current will be explored and evaluated. Other projects include development of measurement methods, measurement of critically needed data, or conduct of fundamental studies of the strain effect, AC loss, stability, and the chemistry and nature of grain boundary weak links.

In HTS electronics, the goal is to establish all the processes required for complex, multi-layer microcircuits which are valuable both for CEEE measurement-development services and for provision of generic technology broadly needed by industry. The major unsolved problem is the controllable fabrication of Josephson junctions. Insulating crossovers, transmission lines, and connections to resistors and semiconductor devices must also be developed. Also the choice of substrates for good epitaxial films must be broadened to include materials with low RF loss.

Technology Transfer Activities

The CEEE superconductivity program has always worked in collaboration with other organizations. Over half of the funding of the LTS program is from other agencies. The HTS program continues this practice. For example, a major project to develop controllable fabrication methods for HTS Josephson junctions is funded by DARPA. The development of low resistance contacts was a joint project with Westinghouse, the development of photo lithography of HTS films was a joint project with AT&T, and there are many other examples. CEEE encourages visiting researchers and is ready to collaborate with other organizations developing materials and needing help with diagnostics.

A major collaboration is being negotiated with the Strategic Defense Initiative Office (SDIO). It is to establish a Manufacturing Operations and Development Integration Laboratory (MODIL) to develop simultaneously the superconducting signal processing electronics for infrared focal plane arrays and the means to fabricate them on a production scale. This project would concentrate first on LTS technology, and move to HTS when it is developed to the point of showing clear advantage. Another collaboration is being negotiated with the National Magnet Laboratory, to study the effect of impurities on flux creep, flux pinning, and other superconducting properties of cuprate superconductors, to be funded by the Office of Naval Research.

The expertise and experience of CEEE in superconductivity is a unique national resource that is available to assist private companies to start programs in superconductivity. A question to be addressed is the relationship to the consortia that are being formed among private companies, universities, and government laboratories. CEEE has much to contribute to each of these, but cannot enter into an exclusive arrangement with any one at the expense of the others. The results of work performed by CEEE must remain largely in the public domain.

Proposed New CEEE Program

Under Projects 1, 3, and 4 below, the first phase of the CEEE component of those projects is described. The work shown has been chosen for maximum impact on the U.S. national effort to develop a commercial HTS technology. All three will apply unique CEEE capabilities in close collaboration with private industry, other national laboratories, and universities.

Project 1. Measurement Methods For Electrical and Magnetic Characteristics

Meetings organized by DOE, DARPA and APS have all concluded emphatically that the published literature in HTS is in chaos because of inconsistency in test and measurement methods and reporting of results. The worst situation arises in measurement of critical current. The measurement of critical current is much more complicated than commonly perceived. Standards based on LTS materials are relevant, but not sufficient for consistent and accurate measurements of HTS materials. At high fields, differences in definitions and test conditions can change results by over an order of magnitude. In low fields, large differences can result from self-field effects. The critical current can also be a function of the magnetic field history, both magnitude and angle. This field hysteresis can give a critical

current which is higher or lower by an order of magnitude. Things are not much better with thin films and devices, especially since the effects of strain, environment, etc. have barely been touched. The emphasis of this project will be on electrical and magnetic tests to support development of practical superconductors.

Project 2. Composition and Structural Analysis

Other parts of NIST, rather than CEEE, will address this area with the special skills that they have.

Project 3. Data for Design and Control of Fabrication Processes

Weak flux pinning is the major stumbling block to the commercialization of HTS, in applications from micro-circuit interconnects to large-scale magnets. Strong flux pinning is the prime requirement for high critical current density. A worldwide effort has been launched in the past two years to commercialize these materials, but until recently little or no effort has been put into the engineered enhancement of the critical current through controlled strengthening of flux pinning, because attainable critical currents were severely limited by other factors. CEEE has world experts in measuring and optimizing flux pinning, gained through two decades experience with this problem in LTS. The program would apply extensive talent and resources to an initial effort to control pinning structures in HTS materials by combining both very recently developed in-situ growth techniques with a multilayer technology. The special application of our expertise in interface control, flux lattice imaging, and multilayer fabrication facilities is expected to have significant impact on the problem. The program is designed to be interdisciplinary, utilizing guest workers and associates from both industry and university research programs.

Project 4. Development of Superconducting Electronic Devices For Measurement Systems

Both Fujitsu and Hitachi have recently announced 4-bit LTS microprocessors (niobium technology) with astonishingly fast clock rates over 1 GHz. With this accomplishment the Japanese have made dramatically clear their substantial lead over the United States in superconducting digital technology. The United States has no program designed to equal or exceed the Japanese capability. This new program will contribute to the remedy of that national weakness.

The program will apply an intense effort to solve the materials-oriented problems of multilayer HTS structures fundamental to the fabrication of HTS integrated circuits. Epitaxial growth of HTS thin films must be sustained through multiple layers of superconductor and insulator with precisely defined interfaces between layers. The fabrication capability will be applied as quickly as possible to prototype digital circuits such as analog-to-digital converters. In parallel will be an effort to develop and understand the potential for digital applications of superconductors using LTS models. One goal of this portion of the program is to bring to the U.S. the best fabrication capability in the world.

Chapter 4 MAGNETICS New Program Plan

Summary

The science and practice of magnetics in the United States has failed to keep abreast of that in other leading countries in spite of the existence of major industrial segments such as magnetic recording (the worldwide market for magnetic recording devices was estimated to be about \$40 billion in 1987). Magnetic technology is recognized to be economically important not only in its own right, but also in terms of the impact it has on a large fraction of the U.S. electronics market and other industrial sectors. Although various studies have called for a variety of U.S. responses, to date none have developed, and the studies continue to warn that we are rapidly losing our ability to compete in magnetics.

The ability on the part of industry to make consistent, accurate, meaningful measurements is essential to a successful U.S. magnetics thrust. Industry is already calling upon NIST to provide infrastructure support for magnetics as it has for semiconductors and many other areas -- providing reference data and materials, developing and disseminating test methods needed by industry for marketplace measurements, contributing to voluntary standards development, providing calibration services for parameters required by industry, and serving as the measurement court of high appeal. NIST can also help industry develop the U.S. standards needed to establish a position for negotiating in the international arena.

The NIST Center for Electronics and Electrical Engineering proposes to respond to industry needs in three major areas.

High Density Information Storage

Although the United States has all but abandoned some markets (e.g., floppy drives), the demand continues to increase, and many new materials and media are appearing to meet the requirements of higher density imposed by the need to support high-data-rate applications; over the last decade, the density of information storage per unit area has about doubled every three years.

To retain or regain an aggressive competitive position, the U.S. magnetic recording industry must find solutions to its measurement needs with respect to present technology and products; the dependence on measurements will become even greater with increasing emphasis on quality control required by advanced recording systems on the drawing board and in development.

For example, the primary parameter for commerce in magnetic media is coercivity, which determines information density or maximum recording frequency. In a collaborative interlaboratory test with industry, NIST has found that the two widely used methods for measuring coercivity produce significantly different results. In response, NIST plans experimental work to identify the physical causes of the wide variation evidenced in coercivity measurements. This study will provide an understanding of the interaction of a given instrument type with the system under measurement and identify those measurement

conditions that need to be controlled. NIST will then build on this work to provide characterization and associated test methods to support advanced recording systems, specifically including high coercivity media.

Following the initial phases of the work on coercivity measurements, NIST plans to develop test methods and associated physical standards for other measurements that industry will need for advanced recording systems, including magnetization and demagnetization parameters, time-dependent effects, and parameters for characterizing thin-film media and hard-disks.

Magnetic Sensing

A very large number of sensors use magnetic principles for evaluation, measurement, or control; these sensors themselves need to be characterized, with increasingly greater accuracy. Nondestructive (NDE) methods utilizing eddy-current techniques for evaluating structures and artifacts can improve both the U.S. competitive stance and well-being. An example of the first is the promotion of efficiency in manufacturing through the identification of flawed starting materials; an example of the second is the promotion of safety in air travel and other transport modes through the detection of incipient structural failure sites without requiring disassembly. In the area of industrial sensing, magnetic systems are needed because of advantages they offer, such as mechanical ruggedness and lack of susceptibility to electromagnetic interference. Field-measuring devices have numerous uses ranging from geomagnetic prospecting and submarine detection to automotive proximity sensors to precision measurement of biomagnetic fields in medicine. All these applications will need calibration and measurement standards to support them.

In response, NIST will develop test methods, physical standards, and supporting calibration services as needed. For example, with respect to NDE, NIST plans to capitalize on its basic invention of a squeezed-crack structure to develop methods for standardizing, characterizing, and calibrating eddy-current NDE coils and the associated probes and instrumentation and to develop methods for characterizing advanced ferrites made from a wide range of materials for NDE probe applications. NIST will also investigate potential applications of magnetostrictive sensors in high stress, high temperature environments for sensing defects or damage in composite structures.

For sensors generally, NIST will develop a theoretical analysis of magnetometry to understand better the problems introduced by the measurement system and the sample geometry due to demagnetization and field images. NIST will then apply the results to the development of standard measurement methods, together with Standard Reference Materials as needed.

Advanced Magnets

Major advances have been made in a wide range of magnetic materials over the last decade. The resulting new capabilities impact the design and production of advanced electronic systems and instrumentation and the transmission and distribution of electric power. Very low temperatures, high frequencies, regions of very high and variable magnetic field are examples of new environments that now need to be considered for magnetic materials and devices. Measurement technology has not kept up with either the advances or the applications. As

a result, a wide range of producers and users of electronic systems need NIST help in measurements supporting for example: magnetic ferrites for high frequency applications and electronic instrumentation; specialty magnetic alloys such as metallic glasses; and permanent magnets, ranging from conventional Alnico through the newer samarium cobalt to the revolutionary rare-earth-based materials such as neodymium-iron-boron.

NIST plans its ultimate response to be the development of test methods needed to support marketplace transactions. For the new powder-produced magnets, for example, NIST will first study the characteristics of powder materials that lead to measurement problems, such as the effect of powder formulations on coercivity, anisotropy, energy product, magnetization stability at both low and high temperatures, and the effects of particle size and distribution and of magnetic interactions among particles. In the second phase, NIST will use his information to develop appropriate test methods.

To support the needs of the electric power industry, NIST will develop new methods for rapidly and accurately determining the relevant magnetic properties of the magnetic steels and new amorphous materials, such as core loss and saturation magnetization.

Introduction

The science and practice of magnetics in the United States has failed to keep abreast of that in other leading countries in spite of the existence of major industrial segments such as magnetic recording. The worldwide market for magnetic recording devices is estimated to be about \$40 billion in 1987, having a compound annual growth above inflation of over 2%, based on the last five years)¹.

"Magnetic materials are an integral part of our modern industrial society, often rivaling semiconductors for breakthroughs in high technology capabilities. They play a key role in power distribution, they permit the interconversion of electrical and mechanical energy, they underlie microwave communication, and they provide both the transducers and the active storage material for data storage in computer-based information systems."

These sentences, taken from Directions in Engineering Research -- An Assessment of Opportunities and Needs, Report of the Engineering Research Board of the National Research Council², document the importance of magnetic technology, impacting a large fraction of the U.S. electronics market and other industrial sectors. U.S. firms shipped \$248

¹Richard D. Balanson "Technical Challenges in the Data Storage Industry," paper given at NIST Colloquium Series/Interface Science Seminar on Information Storage Technology, June 20, 1989. Corroborated by private correspondence from director of U.S. university major magnetics research and development center and approximately consistent with estimates such as those appearing in the Electronics January annual world market forecast issues.

²Directions in Engineering Research -- An Assessment of Opportunities and Needs, Report of the Engineering Research Board, Commission on Engineering and Technical Systems, National Research Council, p. 250; National Academy Press (1987).

billion in the electronics market in 1988³; other sectors impacted by magnetic technology range from motors and generators (In 1988 U.S. firms shipped an estimated \$7.1 billion) to industrial controls (In 1988 U.S. firms shipped an estimated \$5.9 billion)⁴.

Yet this prestigious Board found that

"Despite the many practical uses for the materials, and despite their critical importance to the nation's industry and defense, it has become increasingly clear in recent years that the role of the United States in the science of magnetic phenomena, in magnetic materials, and in magnetic technology has been declining...Since the mid 1970s, American manufacturers have looked increasingly to foreign sources for newer, better, and cheaper magnetic materials and devices. Nations such as Japan have invested far more than the United States has in the R&D needed to advance the performance of magnetic materials."

Robert M. White, then Chief Technical Officer and Vice President of Research and Engineering of Control Data, echoes this view in a 1987 commentary in Physics Today:

"In fact, the whole field of magnetics has largely been ignored by the U.S. science community." "In 1985 the National Academy of Sciences sponsored a study of magnetic materials in the United States through the National Materials Advisory Board. The results of the study showed that although magnetic technology is critical to our economic and strategic well-being, we are rapidly losing our ability to compete."⁵

White goes on to report that

"Recent workshops at Purdue University (sponsored by the Office of Naval Research) and in San Diego (sponsored by DARPA) reached the same conclusion."

And the head of a magnetics group in the U.S. Naval Research Laboratory notes,

"The precarious status of the magnetic recording industry here in the United States vs. Japan is now widely recognized and the amount of time still available to ensure our technological competitiveness is extremely short."⁶

³1989 Electronic Market Data Book, EIA Marketing Services Department, Electronic Industries Association, p. 3 (Washington, DC 1989).

⁴1989 U.S. Industrial Outlook, Chapter 25 Electrical Equipment, pp. 25-1 through 25-4; U.S. Department of Commerce (January, 1989). Much of the product data in this reference is given in terms of 1982 dollars, the chosen reference year. The figures given here in terms of 1988 dollars are computed from the 1982 dollar figures on the basis of a price deflator for the period of 114.4%.

⁵Robert M. White (commentary), Physics Today, Vol. 40, No. 11, p. 89 (November, 1987).

⁶Private communication.

The evidence is in: the state of U.S. magnetic technology is parlous, and the U.S. magnetics industry is under serious market threat from abroad. Various programs are being proposed to address the situation. Inevitably, comparisons are made with the semiconductor industry, and at least one proposal is modeled on the creation of SEMATECH.

For these proposals to succeed, they (like SEMATECH) will need to consider carefully the measurements needed. Industry is already calling upon NIST to provide infrastructure support for magnetics as it has for semiconductors and many other areas -- providing reference data and materials, developing and disseminating test methods needed by industry for marketplace measurements, contributing to voluntary standards development, providing calibration services for parameters required by industry, and serving as the measurement court of high appeal.⁷ Members of the International Disk Manufacturers Association in a recent conference cited the need for coercivity test methods and Standard Reference Materials and invited NIST help and asked for NIST members to participate in their technical committees. In another example, when industry identified the need for a special measuring instrument known as an ac susceptometer, it was able to turn to NIST for the basis of what is now a commercial instrument. In response to needs, NIST has already provided key standards for magnetics that define measured parameters in terms that identify how the measurements of those parameters are to be carried out. Test-method standards and the specifications they support have been used in other technical areas to manipulate international markets. In the words of an executive of the French electronics firm Thomson-CSF,

"If the Japanese control the standard, they can overrun the market."⁸

NIST can help industry develop the U.S. standards needed to establish a position for negotiating in the international arena.

It should be noted that, with industry support and collaboration, centers to develop magnetic recording technology have been established at Carnegie Mellon University (Magnetics Technology Center); at the University of California at San Diego (Center for Magnetic Recording Research); and at the University of Minnesota (Center for Magnetics and Information Technologies). NIST staff have contacts at these centers and monitor their programs, to the degree that information is published. However, these centers increasingly are concerned with research leading to commercial implementation and as a consequence do not conduct substantive generic metrology development. The fact of their sponsorship precludes them from being in a position to provide unbiased reference measurements needed by industry and for commerce.

The remainder of this chapter describes the component of the proposed NIST response to the needs of the magnetics industry falling within the technical competence of the Center for

⁷Fred Fickett, NBSIR 84-3018, Magnetic Measurements, Calibrations, and Standards: Report on a Survey, National Institute of Standards and Technology, formerly NBS (October, 1984).

⁸"Adding Hustle to Europe's Muscle", Business Week Special 1989 Bonus Issue: "Innovation in America", p. 34 (August, 1989).

Electronics and Electrical Engineering⁹. These plans are described under the major headings High Density Information Storage, Magnetic Sensing, and Advanced Magnets. The work is intended to address current and projected industry needs, reflecting priorities identified by industry in the survey carried out by CEEE of magnetic measurements, calibrations, and standards [see footnote 7]; and through numerous contacts at meetings, in visits by NIST staff to industry, and in visits by industry to NIST.

High Density Information Storage

The U.S. market for consumer blank magnetic tape cassettes (video and audio) in 1988 was about \$1.4 billion¹⁰. Magnetic rigid disk drives shipped by US industry (captive and merchant) in 1987 accounted for \$12 billion in a worldwide market estimated to be \$19.5 billion for both floppy and rigid drives¹¹. The demand continues to increase, and many new materials and media are appearing to meet the requirements of higher density imposed by the need to support high-data-rate applications, for example, recording in support of either analog or digital high definition television. Over the past decade or so, the density of magnetic information storage per unit area has about doubled every three years. The United States is losing market share dramatically in some sectors; floppy drives (i.e., those using nonrigid removable media) are an example of a market segment that U.S. industry has all but abandoned.

To retain or regain an aggressive competitive position, the U.S. magnetic recording industry must find solutions to its measurement needs with respect to present technology and products; the dependence on measurements will become even greater with increasing emphasis on quality control required by advanced recording systems on the drawing board and in development.

For example, the primary parameter for commerce in magnetic media is coercivity, which determines information density or maximum recording frequency. On behalf of industry, NIST recently carried out a round-robin evaluation with volunteers from industry and university research laboratories to find out how good or bad practical coercivity measurements are. Industry believes it needs to have the capability to make reliable measurements with accuracies at levels of a few percent (best industry measurements are about 1%). Preliminary analysis of the round-robin data shows an unacceptably large spread in the results (40%), swamping the systematic errors of the two principal instruments used in the tests (vibrating-sample magnetometer and B-H looper). The spread has not yet been explained, but NIST measurements show that the tape specimens used in this study are not the source of these

⁹For indication of scope of CEEE accomplishments in magnetics, see NBSIR 88-3097, Metrology for Electromagnetic Technology: A Bibliography of NBS Publications, section on "Superconductor and Magnetic Measurement," pp. 36 through 55, National Institute of Standards and Technology, formerly NBS (August, 1988).

¹⁰1989 Electronic Market Data Book, EIA Marketing Services Department, Electronic Industries Association, pp. 18, 24 (Washington, DC 1989).

¹¹James N. Porter, "Status and Growth Expectations of Disk Drives," paper given at conference, The Global Business and Technical Outlook for NdFeB Magnet Markets, February 26-28, 1989, Monterey, CA, Gorham Advanced Materials Institute.

large variations. Since coercivity is the most important characteristic for specifying the performance of magnetic recording media, the situation threatens U.S. industry with respect to current technology and raises a warning flag for future advanced, magnetically complex media and recording technologies (e.g., vertical, ceramic, and thin film media; magneto-optical recording), which will need correspondingly advanced measurement support. At least one small company experienced unresolved disagreements with its customers over coercivity measurements and went out of business. Not only is the recording medium itself involved, but also the read/write heads and other auxiliary equipment.

In magnetic recording, the magnetic orientations of individual microscopically small portions of the media, known as magnetic domains, are influenced by the recording magnetic field in a way that results in a net alignment with that field even after the field is removed. As domain sizes shrink in advanced media, new measurement capabilities are needed to understand the role of domain size, to develop the physics of domain behavior, and to characterize domains.

Coercivity

As noted, this property is the basis of commerce in all recording media (and as outlined later, in many other applications of magnetic materials). It varies over a wide range, and different instruments and measurement techniques are required for various parts of the range. The round robin results on ferric oxide recording tape described above indicate a need to investigate the measurement methods currently in industrial use to try to reduce the large variation in measured values of coercivity. To NIST knowledge, no comprehensive program addressing this problem exists elsewhere.

In response, NIST plans experimental work to identify the physical causes of the wide variation evidenced in coercivity measurements. This study will provide an understanding of the interaction of a given instrument type with the system under measurement and identify those measurement conditions that need to be controlled. NIST will then build on this work to provide characterization and associated test methods to support advanced recording systems, specifically including high coercivity media.

Magnetization and Demagnetization Parameters

These are important topics in the commerce of magnetic materials, as they affect practical use. They are of prominent concern in the arena of recording media, where they control how one records on the media, but also in many other applications that call for mixtures of small magnetic particles with nonmagnetic binders, such as microwave absorbers, radiofrequency transformers, and magnetically sealing gaskets (among other uses, refrigerators and freezers). Successful development of methods to measure these parameters will require an understanding of the magnetic properties of the material. These in turn depend on the shape, coercivity, and susceptibility of individual particles; on the interactions among particles, particularly with respect to demagnetization; and the thoroughness with which particles are dispersed. How the properties of the individual particles effect the properties of the composite is not well understood, so that modern formulations are strictly on a recipe basis. For example, it is not

possible in any sense to sum the demagnetizations of individual particles to arrive at the demagnetization of the composite.

As a first step in developing the test methods needed by industry, NIST will seek to establish an understanding of the behavior and characterization of magnetic mixtures. For example, NIST will carry out controlled experiments in which the shapes, magnetic susceptibility, coercivity, and concentrations of the particles will be varied systematically. NIST will use the resulting experimental data as a basis for formulating theoretical models of magnetic mixtures. NIST will then develop computer codes and a catalog of data that will provide the basis for test-method development. As an incidental product of the program, the codes and catalog will be made available for use by scientists and engineers to determine the mixture needed to obtain specific magnetic properties.

Time-Dependent Effects

An understanding of time-dependent effects in the magnetization cycle of magnetic recording media is another area that has been identified as being of great importance to industry. Published determinations of these effects have shown wide variations. These may be caused by physical or chemical differences among samples, differing temperature, mechanical stress, geometry, and instrumental artifacts, especially when long time periods are involved. In response, NIST will experimentally evaluate these time-dependent effects using a new method based on toroidal specimens. NIST will then develop methods for determining and characterizing time-dependent effects and work with industry to institutionalize these methods in voluntary standards developed by organizations such as the American National Standards Institute, the American Society for Testing and Materials, and the Institute of Electrical and Electronics Engineers.

Thin-Film Media

With respect to thin-film media, NIST will develop methods for accurate measurement of magnetization (moment per unit volume) which will account for the uncertain demagnetization factor and the regional demagnetization fields as well as the problems resulting from the multilayer nature of the specimens. To support future technologies, NIST will expand this work to cover magnetic measurements needed for magneto-optical high density optical information storage systems and other high density media.

Hard-Disk Measurements

Hard (rigid) disks pose special magnetic characterization problems to industry, as they involve the intimate contact of magnetic media with aluminum alloys. The nature of the bond affects the properties. At the request of industry, NIST will identify and study the measurement requirements; for example, NIST will modify its scanning tunneling microscope (STM) into a magnetic-force microscope configuration for measurements at very small scales. The projected capabilities of this instrument include imaging. NIST first will conduct interlaboratory experiments with industry to evaluate the status of the measurement methods now in use to characterize magnetic performance and to identify sources of problems known to exist in these methods. NIST will then identify the measurement support that will be required for advanced

hard-disk designs. As the measurement technology develops, NIST will work with industrial standards groups to develop appropriate test methods.

Measurements on Advanced Recording Systems

New magnetic storage media are being developed and introduced; successful implementations are expected to have market implications by the mid 1990s. Many of the new media rely for their properties on physical and magnetic microstructures and effects and on the interactions among them. These media will require new and enhanced measurement capability to support them.

In response, NIST will conduct measurement research to allow standardization of coercivity and magnetization measurement methods to support the introduction of media types that form the foundation of advanced recording techniques, such as perpendicular recording, permanent-magnet-particulate recording, and magneto-optical recording. For example, to develop the basis needed for test methods, NIST plans initially to study the effect of particle size distribution on the magnetic properties of fine-particle nonmetallic media. NIST will also expand efforts to investigate Barkhausen noise effects in thin-film heads used for recording on high coercivity media. Barkhausen noise is produced by the interaction of magnetic domain walls with microdefects and strains and severely degrades head performance. An important tool for these studies is an instrument known as a Kerr microscope that has 0.8-micrometer resolution and a frequency range of dc to 50 MHz. An initial goal will be to identify sources of noise and methods for minimizing it.

Magnetic Sensing

A very large number of sensors use magnetic principles for evaluation, measurement, or control; these sensors themselves need to be characterized, with increasingly greater accuracy. Nondestructive methods utilizing eddy-current techniques for evaluating structures and artifacts can improve both the U.S. competitive stance and well-being. An example of the first is the promotion of efficiency in manufacturing through the identification of flawed starting materials; an example of the second is the promotion of safety in air travel and other transport modes through the detection of incipient structural failure sites without requiring disassembly. In the area of industrial sensing, magnetic systems (magnetoresistive, magnetostrictive, Hall effect, and bubble memory devices) are needed because of advantages they offer, such as mechanical ruggedness and lack of susceptibility to electromagnetic interference. Field-measuring devices (fluxgate and Hall magnetometers, rotating coil devices, and nuclear magnetic resonance probes) have numerous uses ranging from geomagnetic prospecting and submarine detection to automotive proximity sensors to precision measurement of biomagnetic fields in medicine. All these applications will need calibration and measurement standards to support them.

In today's world, instruments for the determination of magnetic properties require calibration over new ranges to support applications of magnetic materials and devices already identified and advanced applications just now emerging. For example, the advent of amorphous ferrous alloys and high temperature superconductors has resulted in an increased demand for

calibration standards for ranges of field, temperature, and magnetic susceptibility not previously felt to be of importance.

Nondestructive Evaluation

The eddy-current NDE community has long been frustrated in its attempts to develop reproducible test specimens for calibrating probes. NIST will capitalize on its basic invention of a squeezed-crack structure to develop methods for standardizing, characterizing, and calibrating eddy-current NDE coils and the associated probes and instrumentation. NIST will also develop methods for characterizing advanced ferrites made from a wide range of materials for NDE probe applications.

SQUID Magnetometers

New magnetometers, based on the Superconducting Quantum Interference Device (SQUID), offer detection of very-low-level magnetism and have become essential to any serious magnetics laboratory. These instruments are manufactured commercially only in this country. Instrumental in development of the SQUID and its applications in magnetometry, NIST plans to develop methods for high precision calibration to match the emerging requirements.

Magnetic Sensor Research

A number of needs with applications to the wide variety of activities alluded to above have been identified. In response, NIST will (1) study field-focussing effects of high permeability transducer elements to increase sensitivity of a wide range of sensors and (2) investigate potential applications of magnetostrictive sensors in high stress, high temperature environments for sensing defects or damage in composite structures.

Magnetometry Instrumentation Standards

NIST will develop the artifact standards (Standard Reference Materials), measurement standards, and calibration services required to support industrial use of ac susceptometers, vibrating-sample magnetometers (VSM), SQUID magnetometers and the B-H loopier. These instruments are used to varying degrees in the measurement of magnetic media, and are basic to almost all of the studies described in this chapter.

NIST will also undertake a program of theoretical evaluation of magnetometry to understand better the problems introduced by the measurement system and the sample geometry due to demagnetization and field images. NIST will then develop standard measurement methods, together with Standard Reference Materials for special applications.

Special Magnetic Measurement Technology Transfer Activities

Because industry needs guidance for applying the many new measurement methods now available to new materials, as well as to old, NIST will review definitions of fundamental parameters and prepare and publish a comprehensive handbook on magnetic measurements.

NIST will also hold workshops on measurements in various fields of magnetics to transfer the NIST-developed technology to industry in a hands-on fashion.

Research in Low-Level Magnetism

Data on, and measurement methods for, very-low-level magnetic effects in materials not commonly regarded as magnetic, such as fiberglass epoxy, are needed by organizations developing sensitive magnetic detection systems for medical, NDE, and military applications. In response, NIST will apply SQUID techniques to the determination of low-level magnetic behavior in materials. NIST will work with industry to identify measurement problems affecting market transactions and then develop responsive test methods.

Advanced Magnets

Major advances have been made in a wide range of magnetic materials over the last decade. The resulting new capabilities impact the design and production of advanced electronic systems and instrumentation. Very low temperatures, high frequencies, regions of very high and variable magnetic field are examples of new environments that now need to be considered for magnetic materials and devices. Measurement technology has not kept up with either the advances or the applications. As a result, a wide range of producers and users of electronic systems need NIST help in measurements supporting for example: magnetic ferrites for high frequency applications and electronic instrumentation; specialty magnetic alloys such as metallic glasses; and permanent magnets, ranging from conventional Alnico through the newer samarium cobalt to the revolutionary rare-earth-based materials such as NdFeB. These new materials for magnets, produced from powders, are becoming significant rivals to the older ones. According to Strnat¹², the world market for permanent magnets in 1987 was \$1.7 billion of which NdFeB represented only 4%. This market is predicted to increase to \$3.5 billion in 1997 with the NdFeB share increasing to 40%.

In the area of electrical power, concerns for efficiency have led to applications of new magnetic materials in products ranging from fractional-horsepower motors to multi-kilovolt-ampere power-system distribution transformers. In vehicular and aircraft transportation systems, for example, there is need for electric motors and generators that produce maximum output for minimum weight. In power transformers, the concern is loss; it is estimated that the average annual capitalized cost of losses in transformers in the United States is about \$2 billion. "The economic impact of power transformer losses is at a state where the cost of evaluated losses over the lifetime of a power transformer often rivals the initial price of the transformer."¹³

¹²"A Global Overview of Rare Earth Magnet Technology," Karl J. Strnat, paper given at conference, The Global Business and Technical Outlook for NdFeB Magnet Markets, February 26-28, 1989, Monterey, CA, Gorham Advanced Materials Institute. Data were quoted from Warlimont of Vacuumschmeltz GmbH, Federal Republic of Germany.

¹³Oskars Petersons and Shirish P. Mehta, NBS Technical Note 1204, Calibration of Test Systems for Measuring Power Losses of Transformers (August, 1985).

Powder-Produced Magnets

In order to develop appropriate test methods, NIST will first study the characteristics of powder materials that lead to measurement problems, such as the effect of powder formulations on coercivity, anisotropy, energy product, and magnetization stability at both low and high temperatures. NIST will also study the effects of particle size and distribution and of magnetic interactions among particles.

High Frequency Ferrites

Building from its extensive experience with ferrite-core coils in eddy-current NDE, NIST will investigate ferrite materials with its new variable-frequency radiofrequency permeameter to discover the source of the observed wide variation in the measured high frequency magnetization. Density and particle-size effects will be investigated. The results of this work will be used to develop needed test methods.

Soft Magnetic Materials

In the area of power engineering, NIST will develop new methods for rapidly and accurately determining the relevant magnetic properties of the magnetic steels and new amorphous materials, such as core loss and saturation magnetization. Among these will be a temperature-variable yoke magnetometer for small samples, which will be a key development for these investigations. Existing quality control and product evaluation techniques require very large samples. The yoke configuration eliminates the need for very large demagnetization corrections required by other methods in high permeability materials.

Chapter 5
LIGHTWAVES: OPTICAL FIBER COMMUNICATIONS
New Program Plan

Summary

Optical fibers are a powerful medium for the transmission of information. They provide high information capacity, high immunity to interference, and high security. The first generation cross-country lines are now installed in the most advanced countries, and the first two trans-oceanic lines have just been placed in operation. Next will come higher performance long-distance lines and new local fiber loops which will connect users directly to the long-distance lines. Based on the structure of the present U.S. telephone system, the local fiber loops will eventually account for 90 percent of all telephone links.

The information handling capacity of optical fiber communications systems is simply enormous. Yet the present state of technology can make use of only one thousandth of that capacity. Much progress remains to be made.

The world market for components for optical fiber communication systems reached \$3.2 billion per year in 1989 and has been growing at about 25 percent per year. The world market for systems is considerably greater. For example, the worldwide investment in undersea lines is expected to reach \$8.5 billion for the eight-year period 1988-1996. Such lucrative markets are promoting intense competition. The U.S. is competitive in optical fibers, but the Japanese are ahead and moving further ahead in the other components. The Europeans have become strong competitors, too. If the U.S. is to compete, it must develop higher performance components with higher quality and reduced cost. All of these aims are highly measurement dependent.

NIST has defined a comprehensive new program for developing measurement support that U.S. industry needs to improve its competitiveness. This measurement support will further research, development, manufacturing, marketing, and use of optical fiber communications systems. For example, NIST measurements will support improvements in quality control, proof of performance in the marketplace, establishment of voluntary industry standards for compatibility and other aims, and entry of U.S. products into foreign markets.

The new NIST program calls for measurement development for three groups of components and technologies. The first group consists of light sources (laser diodes), detectors, and waveguides. The second includes modulators, demodulators, and couplers. The third includes hybrid and integrated optics, materials characterization, multiplexing, coherent communications, switches, amplifiers, long-wavelength fibers, and system performance characterization. To date NIST has received about 20 percent of the funding required for the new program; these funds have enabled NIST to providing partial measurement support for the first two groups of components.

Optical fiber communications is a preeminent technology. U.S. competitiveness in this field is an essential part of U.S. competitiveness in the emerging family of powerful optical technologies, including optical information storage and optical signal processing and computing.

Introduction

Optical fibers are the transmission medium of choice for emerging terrestrial communications systems. Optical fiber communications systems provides high information handling capacity, high immunity to electromagnetic interference, and high data security. The new systems readily accommodate digital encoding of information which provides greatly improved signal quality.

The first generation cross-country lines have already been installed in the most advanced countries, and the first trans-Atlantic and trans-Pacific undersea cables are now in operation. Yet this is only the beginning. Next high performance fiber optic systems will be established, capable of handling much more information. Also, local fiber loops will be established to connect users directly to the long lines, replacing present conventional electronic local loops. The fiber local loops will bring digital signal quality and high information capacity directly to the individual subscribers, whether businesses or individuals. These capabilities will bring new services, such as high definition television and on-demand text, video, and audio for access to worldwide information services, among other applications.

World Market

The world market for optical fibers and supporting components reached \$3.2 billion per year in 1989 and has been growing at about 25 percent per year. The U.S. accounts for \$1.1 billion of this market.¹ The value of installed systems is very high. For example, the first trans-Atlantic undersea line and the first trans-Pacific undersea line cost \$361 million² and \$700 million³ respectively. The U.S. alone has already committed \$2 billion to the development of such lines.⁴

While the growth of the U.S. portion of the world market has slowed as the construction of U.S. long-distance lines has saturated, that growth will pick up again as the local fiber optic loops are developed. Since "local loops account for about 90 percent of the telephone system links in this country",⁵ very large numbers of optoelectronic components will be necessary to convert them to fiber optic capability.

Growth of the international market remains at a high level due to the continued installation of long-distance lines in other countries and to the emergence of both the undersea lines and

¹International Competitiveness Study: The Fiber Optics Industry, Office of Telecommunications, International Trade Administration, U.S. Department of Commerce, p. 25 (September, 1988).

²Howard Rausch, "Undersea Fiber Cables Gain Worldwide Status", Lightwave, p. 48 (February, 1989).

³George Kotelly, "Undersea Lightwave Cable Leapfrogs Pacific Ocean", Lightwave, p. 11 (June, 1989).

⁴Peter Cochrane, "Undersea Fiberoptic Systems Will Benefit From New Technology", Laser Focus, p. 141 (November, 1988).

⁵International Competitiveness Study: The Fiber Optics Industry, Office of Telecommunications, International Trade Administration, U.S. Department of Commerce, p. 34 (September, 1988).

the local loops. The undersea lines alone are expected to grow at 40 percent per year through 1996 and to constitute a worldwide investment of \$8.5 billion over the eight-year period 1988-1996.⁶ For local loops, the worldwide investment will likely be even greater.

U.S. International Competitiveness

International competition to supply the world market for fiber optic components is intense. The Japanese are on a par with the U.S. in fiber technology and are ahead and moving farther ahead in the technology of other key components, such as sources and detectors.⁷ The Europeans are proving to be effective competitors, too. The countries that succeed in providing the high performance components that fiber optic systems need to realize their full potential will gain a tremendous competitive advantage in the marketplace.

If the U.S. is to compete successfully in the expanding world market for fiber optics, it must develop components of high quality, high performance, and low cost. These aims are all highly measurement dependent. The measurement-intensive nature of this field is reflected in the fact that measurements account for 20 percent of the cost of manufacturing optical fiber cable.

NIST's Role

NIST has pursued a new program of measurement support for the U.S. optical fiber communications industry for several years now. That program is aimed at developing the measurement capability needed to support: industrial R&D toward higher performance products; quality control during manufacturing; reduced manufacturing cost; proof of performance in the marketplace; voluntary industry standards for compatibility and other aims; and representation of U.S. interests in international standards-setting activities that affect the sale of U.S. products abroad. Individual companies cannot provide the needed measurement capability. Only NIST has the combination of impartiality and competence in measurement science that enables manufacturers and buyers to work together with NIST to identify key measurement problems and to gain wide acceptance of solutions. International buyers continue to rely on NIST as the official U.S. source of measurement methods critical to acceptance of U.S. products in their markets.

NIST works closely with industry to identify and resolve key measurement problems. NIST responds quickly to industry's measurement priorities, within the limits of NIST's resources. Industry promotes adoption of NIST's measurement methods by incorporating them in voluntary industry standards.

⁶Announcement of "Undersea Fiberoptic Systems and Investment Opportunities", Kessler Marketing Intelligence, p. 1 (May, 1989).

⁷JTECH Panel Report on Telecommunications Technology in Japan - Final Report, Science Applications International Corporation, p. 1-21 (May, 1986). The Japanese Technology Evaluation Program (JTECH) "was initiated in 1983 by the U.S. Department of Commerce; currently the National Science Foundation is the lead supporting agency."

NIST's Plan

NIST is focusing on measurement support for high performance components needed for both long-distance systems and local loops. The performance of these optoelectronic components is the limiting factor in the reliability and the capacity of fiber optic systems. Present systems carry less than one thousandth of the information that the fibers themselves can accommodate.

NIST has been using base resources to develop measurement support for silica multimode and single-mode fibers. NIST has been seeking additional resources since FY 1987 for measurement development for optoelectronic components and related technologies in three groups. Within the three groups, there are six projects. Each project is shown in Table 1 below, and each is described in detail in this document. The order of the projects is the order in which NIST has been seeking funding. That order is determined primarily by the relative timing of industry's needs for measurement support for the components and related technologies. Generally, the components listed first are those needed for the most basic fiber optic systems; those addressed later are needed for more sophisticated systems, many of which are already rapidly emerging.

Table 1
Overview of NIST's Plan

<u>Group</u>	<u>Project</u>	<u>Measurement Support For</u>
Group 1	Project 1	sources, detectors, waveguides
Group 2	Project 2	modulators, demodulators, couplers
Group 3	Project 3	hybrid and integrated optic circuits, materials characterization
	Project 4	multiplexing, coherent communications
	Project 5	switches, amplifiers
	Project 6	long-wavelength fibers, system performance

In the combined budget increases in FY 1987, FY 1988, and FY 1989, NIST has received partial funding of Projects 1 and 2. No funding has yet been received for Projects 3 through 6.

The following discussion describes in detail the work that will be undertaken in each of the six projects.

Project 1: Sources, Detectors, and Waveguides

Laser diodes and light emitting diodes are the sources that create the light sent down optical fibers. Detectors capture the light at the receiving end and convert it to an electrical signal for subsequent processing. Waveguides are optical paths embedded in optically active

materials. The waveguides channel light in desired directions and transfer it from one path to another.

To provide measurement support for sources, NIST is developing measurements for key laser diode characteristics including pulse width and speed, linewidth⁸ to 0.1 part per million (ppm), wavelength to 0.1 ppm, and power output. In a new program, NIST will correlate key aspects of device design with linewidth and will measure linewidth and wavelength to closer tolerances in preparation for the coherent component of the work in Project 4 on Multiplexing and Coherent Communications. NIST will also develop measurements for diode spectral purity, modal noise, threshold current, and stability.

To provide measurement support for detectors, NIST is developing measurements for a first set of parameters needed to characterize detectors, including spectral responsivity (sensitivity as a function of frequency), uniformity of response over the detector's surface, and speed and linearity of response. In a new program, NIST will develop measurement support for electronic noise in detectors, performance of detector/amplifier packages, and fabrication of special detectors to enable correlation of key aspects of design with noise performance and sensitivity. Noise measurements are especially important since improved noise performance reduces errors in transmission and enables reduction of the numbers of repeaters (re-amplification stations) along an optical fiber communications line. That reduction in turn reduces the cost and increases the reliability of the line.

To support waveguides, NIST is developing measurements and theory for attenuation and mutual coupling in the guides, and measurements for index profile. In a new program, NIST will develop time-domain reflectometry techniques that will enable determining the performance and defects in optical waveguides. Also, NIST will extend its measurement development beyond the present materials supported, glass and lithium niobate, to compound semiconductors. NIST will also construct a facility to house equipment to prepare optoelectronic materials and devices needed for measurement development for sources, detectors, and waveguides.

Project 2: Modulators, Demodulators, and Couplers

Modulators place information on the lightwaves that are sent down optical fibers. Demodulators remove that information at the point of reception. The rate at which modulators and demodulators perform their functions is one of several factors that determine the information handling capacity of a fiber optic system. Couplers join optical fibers together and must transfer light with minimum loss to keep signal strength strong. They require mechanical precision and special optical interface technology to perform their function efficiently.

⁸Linewidth here means the spread in frequency of a laser diode. That is, laser diodes do not put out a pure single frequency. For example, a typical laser diode operates at 200 THz (200,000,000 MHz) and has a linewidth of 100 MHz. Thus it generates light from a low frequency of (200 THz - 50 MHz) to a high frequency of (200 THz + 50 MHz).

For measurement support for modulators and demodulators, NIST is developing measurements for the dominant method of modulation, pulse code modulation. Special emphasis is being given to measurements for characterizing discrete lithium niobate modulators, with focus on modulation depth and modulation speed. In a new program, NIST will extend measurement support to additional types of pulse code modulators: integrated compound-semiconductor modulators, and integrated superlattice compound-semiconductor modulators. Progress in this project will facilitate NIST's entry into the related but more difficult area of modulation requirements for coherent systems. That topic will be addressed in Project 4 on Multiplexing and Coherent Communications.

For couplers, NIST is developing measurements for losses in "passive" couplers that joining both single-mode optical fibers and multimode optical fibers. In a new program, NIST will enable extend its work on "passive" couplers to include measurements for bandwidth and coupling geometry. NIST will also develop measurement support for "active" couplers. Active couplers incorporate active devices, such as sources and amplifiers, right into the structures of couplers. The work on active couplers ties into and supports the work in Project 5 on Switches and Amplifiers.

Project 3: Materials Characterization and Integrated-Optic Circuits

Lack of measurement methods and verified data for characterizing electrically active materials is hampering the development and application of new optoelectronic devices. Both discrete and integrated-optic devices are affected, but the need for materials data is especially critical for integrated-optic circuits. Lithium niobate and glass will be used in discrete components. Compound semiconductors, such as gallium arsenide, will be used in discrete components and in integrated-optic circuits.

In a new program, NIST will provide measurement support for lithium niobate, glass, and compound semiconductor integrated optic circuits. For lithium niobate, NIST will develop measurement techniques for surface roughness and for electro-optic, acousto-optic, magneto-optic, and thermo-optic properties. For glass, NIST will develop measurement techniques for attenuation, coupling losses, cross-talk, and switching efficiency. For compound semiconductors, NIST will focus on measurements for attenuation, coupling losses, bandwidth, cross-talk, and switching efficiency.

Project 4: Multiplexing and Coherent Communications

Multiplexing and coherent techniques enable increasing the amount of information sent through an optical fiber communications system. Multiplexing means combining different optical signals together at the point of transmission for more efficient handling. That process is reversed at the point of reception where the signals are separated from each other. Coherent techniques enable many different signals, each of which may contain many multiplexed signals, to travel down an optical fiber simultaneously and to be separated readily at the receiving end by tuning, much as a radio or television set tunes. Coherent techniques enable a thousand-fold increase in the amount of information carried by optical fiber communications systems, compared to present technology. Coherent techniques also enable increasing the sensitivity of the receivers at the end of optical fiber lines by a factor of 10

or greater. This improvement reduces the number of repeaters (amplification stations) required in long-distance lines. The reduction in the number of repeaters lowers system costs and increases system reliability. High system reliability is particularly important for transoceanic systems since repairs of repeaters will be extremely expensive. Coherent techniques will also be important for local loops where signal strength will be degraded by repeated subdivision of signals for the multiple branches of the loops.

In a new program, NIST will provide measurement support for multiplexing and for coherent systems. The performance of a coherent system requires precise control of the frequency and the phase of the light in the system. To help achieve this control, NIST will develop absolute frequency standards and related transfer standards to enable transfer of precise values to industry. Also, highly accurate measurements for phase noise will be developed. For multiplexers, NIST will focus first on electrical techniques for multiplexing. Then NIST will move quickly to optical techniques using discrete components and finally to optical techniques using integrated-optic circuit components. Wavelength-division multiplexing will be the key technique addressed. Key parameters that require measurement support include cross-talk, attenuation, coupling efficiency, bandwidth, and polarization.

Project 5: Switches and Amplifiers

Optical switches control the passage and direction of signals through an optical communications system. Optical amplifiers restore the strength of weak optical signals that must travel long distances or that must be subdivided many times for the multiple branches of local loops.

In a new program, NIST will focus on measurement of switching times, with resolution to 10 picoseconds initially, and later to 1 picosecond. The speed of switches is one of the key factors limiting the rate of information handling by an optical fiber communications system. After addressing switching time, NIST will develop measurements for other important parameters of switches, such as efficiency and on/off voltages. For amplifiers, NIST will focus on measurements of bandwidth and noise first, then gain, heterodyne responsivity, and linearity.

Project 6: Long-Wavelength Fibers and System Performance Measures

Current optical fibers, based on silicon dioxide (silica), have attenuation as low as 0.2 dB per kilometer. New long-wavelength fibers, based on halides, are under development. They offer reduced levels of attenuation down to 0.001 dB per kilometer. These fibers will operate at wavelengths of 1.8 to 3.0 micrometers, compared to the present 1.3 and 1.55 micrometer wavelengths of silicon dioxide fibers. The new long-wavelength fibers are important to long-distance lines, especially transoceanic lines, since they will reduce the number of repeaters (amplification stations) required by the line. This reduction will increase system reliability and reduce system cost.

As the performance and complexity of optical fiber systems increases, the industry will need more powerful methods for verifying and maintaining that performance. In particular, industry

will need objective measures applicable both to long-distance lines, including the transoceanic lines, and to local loops.

In a new program, NIST will develop special methods for determining the unusually low levels of attenuation in long-wavelength fibers. These methods will affect research and development, marketing, and design of systems employing the fibers. As these fibers come into service, NIST will have to provide special methods for characterizing their numerical aperture, spot size, and cut-off wavelength. For system performance measures, NIST will develop accurate measurements of bit error rates. NIST will focus first on detailed studies aimed at proper interpretation of "eye diagrams", a sensitive analog technique for qualitatively assessing bit error rates. Later, NIST will develop more comprehensive digital techniques that will give precise quantitative assessments of bit error rates in optical fiber systems.

Chapter 6
LIGHTWAVES: OPTICAL FIBER SENSORS
New Program Plan

Summary

Sensors are measurement devices. They provide information needed by instruments and control systems. Sensors serve diverse systems including home appliances, automobiles, airplanes, automated manufacturing, and the national power grid. Sensor systems are the analog of the human nervous system for physical systems. Their capabilities are often the limiting factors in the performance of high technology systems.

Optical fiber sensors are a powerful class of sensors. They bring to measurement systems many of the advantages that optical fibers have brought to communications systems. For example, optical fiber sensors offer fast response times and high information capacity. Also, their non-electrical nature makes them immune to electrical interference, a particular advantage as systems become more complex. Fiber sensors can perform the functions of virtually any conventional sensor, often faster and more sensitively and usually in a package that is smaller, lighter, and easier to apply. They can perform measurement tasks that are impractical or impossible with conventional sensors. For instance, they can be embedded in critical structures, such as airplanes, ships, or buildings. There they can report continuously on the health of the structures while in service, giving warning before failure, and possibly averting disaster.

Optical fiber sensors are a growing part of the expanding market for sensors. The present world market for optical fiber sensors is about \$125 million and represents about 5% of the world market for all types of sensors. By the year 2000, the world market for optical fiber sensors will exceed \$1 billion and will represent about 20% of the world market for all sensors.

Optical fiber sensors have tremendous potential for measuring a wide variety of quantities important to military and aerospace systems, medicine, manufacturing, transportation, energy, and many other fields. However, realization of their potential will require special measurement support for sensor development, manufacture (including standardization), marketing, and use. CEEE will apply its available resources to provide as much of that support as possible for optical fiber sensors used to measure electric and magnetic quantities. CEEE will stress development of: measurement methods for sensor properties, and measured reference data for the electro-optic and magneto-optic properties of materials critical to sensors.

Description of Fiber Sensors

The sensing mechanism used by an optical fiber sensor may be internal or external to the fiber. When internal, the sensing mechanism is intrinsic to the fiber or is incorporated into the fiber during manufacture. When external, the sensing mechanism is located in a material applied to the fiber or in a separate material to which the fiber carries light. The use of an external sensing mechanism sometimes permits achieving higher sensitivities or other improvements relative to an internal mechanism. In all cases, the sensor functions to change

the properties of the light transmitted through the fiber in a way that can be detected and interpreted in a quantitative manner. Fiber sensors can be designed to measure quantities at individual points or continuously over the length of the fiber sensors.

Fiber sensors can measure a wide variety of quantities of interest. A least four classes of quantities can be measured, as well as a number of other individual quantities.

Table 1
Quantities Measured

<u>position</u>	<u>movement</u>	<u>other</u>
displacement/level angle	velocity/flow rotation vibration/sound acceleration	radiation strain force
<u>thermodynamic/chemical</u>	<u>electric and magnetic</u>	
temperature pressure acidity (pH) chemical composition ¹	electric field/voltage magnetic field/current power energy	

Fiber sensors have many advantages, both intrinsic and potential, relative to other types of sensors.

Table 2
Advantages of Optical Fiber Sensors

<u>Intrinsic Advantages</u>	<u>Potential Advantages</u>
immune to electromagnetic interference non-perturbing to environment being measured secure (difficult to tap) compatible with fiber telemetry high data rates geometric flexibility tolerant of extreme environments small size low weight electrical isolation	sensitivity dynamic range reliability long shelf life low maintenance low cost modularity

In their present stage of development, fiber sensors for different measured quantities vary widely in their success in achieving all of the "potential advantages" listed above. A key goal for the further development of fiber sensors is to realize all of the potential advantages for all quantities that they measure, to the extent possible.

Fiber Sensor Market

Sensors of all types are an enabling technology that support a U.S. market of \$50 billion to \$75 billion per year of automated controls, according to the National Research Council.² Sensor performance is often the limiting factor in the performance of the systems that the sensors support.

U.S. Market

Estimates of the size of the U.S. market for fiber sensors are shown in Table 3 along with the sources of the estimates. The first source shows a smaller 1988 market than the second but reflects a higher out-year growth rate (39% versus 18% per year).

Table 3
U.S. Market for Fiber Sensors

<u>Source/publication date</u>	<u>1988</u>	<u>1992</u>	<u>1993</u>	<u>1996</u>	<u>1998</u>
Corporate Strategic Intelligence 1989 ³	37	134		507	
Business Communications Co. 1989 ⁴	67		170		381

According to Corporate Strategic Intelligence, four fields of application are expected to account for 89% of the U.S. market for optical fiber sensors in 1996, as shown in Table 4: military/aerospace, biomedical, process control, and transportation.

Table 4
U.S. Market for Fiber Sensors in 1996
By Field of Application⁵

	<u>\$Millions</u>	<u>Percent</u>	
Military/aerospace	245	48	} 89%
Biomedical	99	20	
Process control	76	15	
Transportation	31	6	

Energy/metals	10	2	
Research & development	7	1	
Test/measurement	5	1	
Robotics	5	1	
Security systems	2	1	

Others	27	5	
Totals	<u>507</u>	<u>100</u>	

World Market

The world market has been projected by several sources, as shown in Table 5. It appears likely that the world market will exceed \$1 billion by the year 2000. [The figures shown for the year 2000 were not provided by the sources listed; rather they were calculated by extending to the year 2000 the average compound annual growth rates implied by the two nearest years with data.]

Table 5
World Market for Fiber Sensors (\$Million)

<u>Source/publication date</u>	<u>1988</u>	<u>1990</u>	<u>1993</u>	<u>1995</u>	<u>1998</u>	<u>2000</u>
Kessler Marketing Intelligence 1987 ⁶			278			
International Resource Development 1987 ⁷		125		415		[1400]
Market Intelligence Research Co. 1988 ⁸		150	275			[1100]
Business Communications Co. 1989 ⁹	122		313		814	[1200]

According to Business Communications Co., three areas of application are expected to account for 85% of the world market for optical fiber sensors in the year 1998, as shown in Table 6: military/aerospace, medical, and industrial.

Table 6
World Market for Fiber Sensors (\$Million)
By Field of Application¹⁰

	<u>1988</u>	<u>1993</u>	<u>1998</u>	<u>Avg. Growth (%)</u>
Military/aerospace	34	110	300	} 85% 24
Medical	70	140	281	
Industrial	15	40	110	

Others	3	23	123	45
Totals	<u>122</u>	<u>313</u>	<u>814</u>	

Optical fiber sensors are expected to become an increasingly important part of the market for all types of sensors, as shown in Table 7. Fiber sensors constitute 5% of the market for all sensors worldwide at the present time and appear likely to constitute 20% by the year 2000. The world market for all sensors is expected to be \$6 billion to \$7 billion in the year 2000. [The figures for the year 2000 were not provided by the sources cited; rather they were calculated by extending to the year 2000 the average compound annual growth rates implied by the two nearest years with data.]

Table 7
Fiber Sensors Versus All Sensors in the World Market (\$Million)

<u>Source/publication date</u>	<u>1988</u>	<u>1990</u>	<u>1993</u>	<u>1995</u>	<u>1998</u>	<u>2000</u>
International Resource Development 1987 ¹¹						
Fiber sensors		125		415		[1400]
All sensors		1790		3300		[6100]
Percent fiber sensors		7%		13%		[23%]
Business Communications Co. 1989 ¹²						
Fiber sensors	122		313		814	[1200]
All sensors	2300		3857		5962	[7100]
Percent fiber sensors	5%		8%		14%	[17%]

U.S. Competitiveness

Information on U.S. competitiveness in fiber sensors is sparse. The NSF-sponsored Japanese Technology Evaluation Program (JTECH), however, found in 1986 that the Japanese were ahead and gaining further ground in the closely related technology of fiber optics communications in all phases: basic research, advanced development, and product development.¹³

Examples of Applications

Both existing and emerging applications of fiber sensors are critically important to a number of fields. Some examples follow:

In aerospace systems, fibers promise "smart skins" for aircraft. They can sense electromagnetic events, such as radar scans, or mechanical events such as flexing under stress, possibly in time for corrective action to be taken.¹⁴

In the biomedical area, fiber sensors can determine the concentration of oxygen in hemoglobin by sensing its color.¹⁵

In process control, fiber sensors already monitor temperature, pressure, flow rates, liquid levels, and other quantities in difficult processing environments. They are destined for expanded applications.

In robotics, fiber sensors can provide a sense of touch (pressure) and temperature.

In energy, fiber sensors may provide improved means for controlling and optimizing the efficiency of the national power grid.

In the U.S., many of the most sophisticated applications of fiber sensors have been made by the U.S. Government. For example, DOD is aggressively pursuing the development of optical fiber gyroscopes (rotation sensors) which have no moving parts. DOD is already using fiber

sensors as underwater microphones (hydrophones) for submarine detection in Project Ariadne.¹⁶ DOE is using fiber sensors to support nuclear weapons testing and nuclear effects simulation.

Technical Challenges

There are several technical challenges that must successfully be addressed before optical fiber sensors can have their maximum economic effect. Those challenges fall into five groups. Three of these groups relate to sensor development itself and thus to the "potential advantages" of sensors, as described above; these three groups are performance, cost, and modularity/standardization. The remaining two groups relate to signal handling issues that affect optical systems more broadly; they are networking/multiplexing and optical signal processing. The details are shown in Table 8.

Optical Fiber Sensors Vs. Electronic Sensors

Electronic sensors will continue to coexist with optical fiber sensors indefinitely. The performance of electronic sensors is well established. Also, electronic sensors are well supported by electronic methods for signal handling (multiplexing, networking, and processing), a distinct advantage. Electronic sensors are typically used as part of control systems which will themselves remain electronic for the foreseeable future.

Because of the special capabilities of optical sensors, they will increasingly replace conventional electronic sensors as the challenges related to sensor development (performance, cost, modularity, and standardization) are successfully addressed. Electronic methods of signal handling can serve optical fiber sensors well since the optical signals they generate can be readily converted to electrical form. At a future time, all-optical methods of signal handling will be available to complement the capabilities of the optical fiber sensors.

Measurement Implications

The technical challenges above give rise to a variety of measurement-related needs. CEEE focuses on measurement needs associated with:

- general properties of fibers that affect implementation of fiber sensors broadly
- specific properties of fibers for sensing electromagnetic quantities

CEEE does not address specific properties of for sensing other quantities. The key measurement-related needs that CEEE must address fall into two categories: improved measurement methods and measured reference data. The specific needs in each of these categories are shown in Table 9.

Table 8
Technical Challenges for Optical Fiber Sensors

Sensor development:

performance

accuracy In some applications, such as revenue metering for the electric power industry, fiber sensors must have very high accuracy. The fundamental limits to accuracy are set by materials properties and their variation with environmental conditions.

sensitivity For some measured quantities, fiber sensors are among the most sensitive available; but in other cases higher sensitivity is needed. High sensitivity requires full exploitation of the properties of existing and new materials and the use of special manufacturing techniques.

selectivity The optical properties of materials are sensitive to environmental influences other than those that are to be measured. Sensors must be made insensitive to quantities not to be measured.

dynamic range Fiber sensors must often measure key quantities over a wide range of values. Materials properties must be exploited in refined component designs to achieve this goal.

reliability In many of the applications for which fiber sensors provide the greatest benefits, they will be subjected to adverse environments. Sensors must be resistant to broad temperature ranges, vibration, high pressures, and ionizing radiation.

cost Reduction in the costs of fiber sensors will require improvements in design and manufacturing processes.

modularity/standardization Fiber sensors must be reduced to standardized, modular, plug-in forms for both electronic and optical systems. This is necessary to enable easy substitution in present day electronic control systems and to enable incorporation into emerging all-optical control systems.

Table 8 (continued)
Technical Challenges for Optical Fiber Sensors

Signal handling:

networking/multiplexing	Fiber sensors must be successfully multiplexed and networked in all-optical systems to serve in emerging applications that require multiple sensors, equivalent to sophisticated "nervous systems".
optical signal processing	The emergence of optical signal processing will enable the optimum utilization of optical fiber sensor data at the high data rates that the sensors can produce.

Table 9
Measurement-Related Needs For Fiber Sensors

<u>Need</u>	<u>Description</u>
Improved measurement methods:	
polarization	transverse electric field direction of light traveling down a fiber
birefringence	index of refraction ¹⁷ versus polarization for light passing through materials
multiplexing	performance of multiplexing systems for fiber sensors
Measured reference data:	
birefringence	
magneto-optical coefficient	response of materials to magnetic fields
electro-optical coefficients	response of materials to electric fields

Sensors that measure electric and magnetic fields, and the closely related quantities of voltage and current, work by causing a change in the polarization of the light traveling through a fiber. Thus precise measurements of polarization are critical in determining sensor performance, particularly accuracy, sensitivity, and selectivity. Also, birefringence measurements are needed especially for evaluating materials for polarization-preserving fibers;

these fibers use high birefringence to produce their polarization-preserving behavior. Polarization-preserving fibers carry light to and from special sensing materials that shift polarization in response to the quantity of interest.

Measured reference data are needed for specially treated fiber materials, separate sensing materials, and optical components used in building optical fiber sensors. These data support the design of sensors with high performance levels and low cost. For example, measured data are needed for the magneto-optic and electro-optic coefficients of materials. High coefficients are necessary to maximize sensitivity to electric and magnetic fields. Also, measured data are needed for the variations of these coefficients with frequency to support sensor use over wide ranges of frequency. Measured data are needed for the variation of the coefficients with temperature and stress, the two environmental quantities most likely to create measurement errors in today's optical fiber sensors for electric and magnetic quantities. Measured data are needed for fibers with low birefringence for use in magnetic field and current sensors, and for fibers with high birefringence for use in polarization-preserving fibers. More generally, measured data are needed for the standardization of sensors in modular form.

At a future time, CEEE may develop measurements for the performance of multiplexing schemes used to accommodate multiple sensors. Particularly important are measurements of the effects of multiplexing on the accuracy of the measurements made by sensors. For example, one multiplexing scheme requires sending a light pulse down an optical fiber that interconnects multiple sensors; each sensor returns a separate pulse that arrives back at the source at a different time, depending on the distance of the sensor from the source. The intensities of the returned pulses contain the information on the measured quantity and may be affected by the multiplexing scheme.

CEEE has no plans at the present time to provide measurement support for networking or optical computing as part of the optical fiber sensor work. Rather, CEEE's new program of measurement support for optical fiber communications, described in Chapter 5, will provide measurement support for characterizing the performance of individual components and overall systems for optical fiber networks. Measurement support for optical computing is not yet a part of CEEE's formal plans, but the needs of this emerging field are being monitored.

With funds provided by other Federal agencies, CEEE will continue to meet their special measurement requirements related to sensors. Those requirements often call for development of special optical fiber sensing elements for key quantities, such as magnetic fields and electric current, or for development of measurement techniques specifically adapted to optical systems. Measured data may be required on the effects of environmental factors, particularly radiation, on the performance of fiber sensors. Present requirements of the other agencies focus on measurements of alternating currents at low frequencies (60 Hz) for power measurement, at intermediate frequencies (1000 Hz to 100 MHz) for measurement of power systems pulses, and at very high frequencies (up to 1 GHz or 10^9 Hz) for immunity testing for electromagnetic interference. In addition to their interest in measurement of electric current, the other agencies have had a long standing interest in measurement of electric fields and voltage. Further, they are now becoming interested in measurement of magnetic fields.

Appendix 1
SENSING MECHANISMS OF OPTICAL FIBER SENSORS

The diversity of techniques used to measure different quantities with optical fiber sensors is considerable, but most of these techniques result in translating the quantity of interest into one of four principal changes in the light in a fiber. This change must be measured correctly and interpreted in terms of the change in the quantity of interest.

Table 10
Mechanisms of Optical Fiber Sensing

intensity	change in strength of lightwave as it travels down the optical fiber
wavelength	change in color of the light
phase	shift in location of the waveform maximum
polarization	change in direction of transverse electric field

The sensing action may occur in the fiber itself or in a material that is used with the fiber and that is optimized to sense the quantity of interest.

Examples of intensity, wavelength, and phase mechanisms

Intensity is useful for measuring a wide variety of quantities, including mechanical, chemical, and thermal quantities. For example, pressure can be measured because transverse pressure applied periodically along a fiber increases optical loss. Similarly, bending can be measured because bending a fiber to a small radius increases its loss. Temperature can be measured by incorporating certain materials, especially rare earth elements, into a fiber to make its loss temperature sensitive. The presence or concentration of liquids or gases can be measured by making the outer parts of a fiber slightly porous to induce a loss dependency. Both temperature and pressure can be measured through their effects on losses at interconnections between two fibers or between fibers and other components. Intensity sensors are very versatile. They are also among the least complex and costly of sensor types.

Wavelength is useful for measuring temperature, and perhaps other quantities. At least three different mechanisms for measuring temperature are already providing the basis for existing commercial instrumentation. The first mechanism works by measuring the temperature-dependent intensity and wavelength distribution of the radiation produced by any warm body. The radiation may be generated by the fiber itself or by another component used in conjunction with the fiber. The second mechanism works by measuring the temperature-dependent fluorescence from a material. Fluorescence is the emission of light by a material in response to illumination by other light. The third mechanism works by measuring the temperature-dependent Raman effect of a material. The Raman effect is the emission of light of a slightly different wavelength in response to illumination by other light.

Phase is useful for measuring strain. Phase can also be used to measure other quantities that induce strain, including temperature, pressure, and even electric and magnetic fields. In a phase sensor, the fiber sensing element is made part of an interferometer; the interferometer is a device that is sensitive to the small changes in the length of the fiber, caused by strain. Phase sensors are among the most sensitive of optical fiber sensors. A fiber only 1 meter in length can be used to detect a strain as small as 1 part in 10^{14} .¹⁸

Polarization mechanism

Polarization is the primary sensing mechanism used for electric and magnetic quantities. Therefore, it is the principal mechanism of concern to NIST's Center for Electronics and Electrical Engineering. When electric fields or magnetic fields are applied to the sensors, the nature of the polarization of the light changes with the applied field.

Magnetic fields: For sensing magnetic fields, the change in polarization is caused by the Faraday effect. The Faraday effect is observed when a magnetic field is applied parallel to the fiber and polarized light is launched into the fiber. The polarization of the light is rotated in proportion to the strength of the applied magnetic field and to the distance that the light travels in the fiber. A constant of proportionality describes the sensitivity of the fiber to this change and is called the Verdet constant. Thus linearly polarized light launched into one end of the fiber will remain linearly polarized, but its direction of polarization will be rotated in proportion to the strength of the applied magnetic field on the fiber.

Electric fields: For sensing electric fields, the change in polarization is caused by the Pockels effect. The Pockels effect is observed in certain crystalline materials used in conjunction with fibers to form fiber sensors. The Pockels effect is not observed in fibers themselves; they are not crystalline. Linearly polarized light flowing through the special crystalline materials will alternately become circularly and linearly polarized. Each time it becomes linear, the linear axis will appear at a right angle with respect to its previous appearance. The distance over which this change takes place is a function of the strength of the electric field applied to the crystalline material. The strength of the Pockels effect in a given material is measured by electro-optic coefficients that are sometimes called the "r" coefficients.

ENDNOTES

1. Chemical composition measurements are accomplished by several methods, including measurement of the index of refraction of a material, or measurement of the frequency of light from fluorescence that is induced in the material by light sent down the fiber.
2. Photonics: Maintaining Competitiveness in the Information Era, National Research Council, National Academy Press, Washington, DC, p. 51 (1988). The quoted market for automated controls is assumed to be the U.S. market, also.
3. Ashok Bindra, quoting data from Corporate Strategic Intelligence Co. (Middlebush, N.J.) in "Fiber-Optic Sensors Find New Markets", Electronic Engineering Times, p. 100 (May 22, 1989).
4. From an announcement of a new study by Alan Hall, "New Markets in Fiber Optic Sensors", Business Communications Co., Inc. (Norwalk, Connecticut, p. vi (October, 1989).
5. Ashok Bindra, quoting data from Corporate Strategic Intelligence Co. (Middlebush, N.J.) in "Fiber-Optic Sensors Find New Markets", Electronic Engineering Times, p. 100 (May 22, 1989).
6. The data from Kessler Marketing Intelligence were reported by Paul Semple in "Marketing Report", Fiberoptic Product News, p. 33 (March, 1987).
7. The data from International Resource Development, Inc. were reported by Paul Semple in "Marketing Report", Fiberoptic Product News, p. 33 (March, 1987).
8. The data from Market Intelligence Research Company were reported by Otis Port and were read from a graph with a rather broad line (about \$25 million thick). The article does not specify whether the U.S. or the world market is being addressed, but the world market may be safely assumed. Otis Port, "Now Fiber Optics Can Hear and Feel, Too", Business Week, p. 168A (December 5, 1989).
9. From an announcement of a new study by Alan Hall, "New Markets in Fiber Optic Sensors", Business Communications Co., Inc. (Norwalk, Connecticut, p. vi (October, 1989).
10. From an announcement of a new study by Alan Hall, "New Markets in Fiber Optic Sensors", Business Communications Co., Inc. (Norwalk, Connecticut, p. vi (October, 1989).
11. The data from International Resource Development, Inc. were reported by Paul Semple in "Marketing Report", Fiberoptic Product News, p. 33 (March, 1987).
12. From an announcement of a new study by Alan Hall, "New Markets in Fiber Optic Sensors", Business Communications Co., Inc. (Norwalk, Connecticut, p. vi (October, 1989).
13. JTECH Panel Report on Telecommunications Technology in Japan - Final Report, Science Applications International Corporation, p. 1-21 (May, 1986). The Japanese Technology Evaluation Program (JTECH) "was initiated in 1983 by the U.S. Department of Commerce; currently the National Science Foundation is the lead supporting agency."
14. Otis Port, "Materials That Think for Themselves", Business Week, pp. 166-167 (December 5, 1988).
15. Otis Port, "Now Fiber Optics Can Hear and Feel, Too", Business Week, p. 168A (December 5, 1988).
16. Otis Port, "Now Fiber Optics Can Hear and Feel, Too", Business Week, p. 168A (December 5, 1988).

17. The index of refraction is a pure number ratio that indicates how much a material slows down the speed of light passing through it compared to the speed of light in a vacuum (outer space). Light travels fastest in a vacuum. Thus a material with an index of 2 slows down light by a factor of 2 relative to its speed in a vacuum.

18. Robert S. Mellberg, "Fiber-Optic Sensors", Stanford Research International, Research Report No. 684, p. 3 (Summer, 1983).

Chapter 7
LIGHTWAVES: LASERS
New Program Plan

Summary

Lasers are surfacing in commercial products with world markets of billions of dollars per year. As they do, the U.S. is progressively losing market share in the world commercial market for lasers. In the five years from 1982 to 1987, the U.S. share of that market fell from 75% to 38%. Japan and Europe picked up the entire difference in roughly equal amounts. Similarly, the U.S. is losing market share in the world commercial market for laser optics. From 1984 to 1988, the U.S. share of that market dropped from 64% to 45%. Laser optics include components such as lenses and mirrors that are critical to laser performance.

The intent of other nations is clear; both Japan and Europe have launched programs to advance their competitiveness in the laser technology required for commercial applications of lasers.

Lasers are high technology, indeed. As such, they require extra effort to apply. In return they deliver impressive gains in productivity and performance. Lasers have demonstrated their capabilities in many commercial applications, including these: manufacturing, especially materials processing; research and development; medicine; communications; optical memories, including audio compact disk players, video players, and data storage devices; printing; test and measurement, including environmental sensing; inventory control using barcode scanners; and many other fields. For example, in manufacturing, lasers can cut and drill materials with incredible precision, speed, and economy; lasers are the tools that never dull. In medicine, lasers provide the least invasive of surgical procedures. Already, they are used in sixteen fields of medicine. Eventually, they may be used in 10% to 40% of all surgical procedures. In optical memories, lasers provide the highest information densities yet achieved by any form of data storage; and further advances are promised.

The world market for lasers and laser-based products exceeds \$14 billion per year, and likely by a wide margin. Laser sales themselves are about \$2 billion per year. Sales of just three laser-based products account for \$12 billion per year: optical memories (\$6.6 billion by Japan alone), laser printers (\$3 billion), and barcode scanners (\$2.5 billion). Sales levels for many other laser-based products are not known but are likely highly significant, especially for manufacturing equipment and medical equipment which consume high dollar volumes of lasers. Japan's ascendancy in the markets for laser-based products is evident. Japan supplies 90% of the world market for audio compact disk players and 85% of the market for low-end laser printers.

The economic implications of success in the commercial markets for lasers and laser-based products will continue to be highly significant. Both present and emerging applications assure that fact. Here are several examples. The world market for optical data storage devices is expected to increase ten fold in just four years from \$2.0 billion in 1988 to \$22 billion in 1992. Contemplated laser-based surgical procedures for eyesight correction have a projected market of \$6 billion per year. Barcode scanners have a present market of \$2.5 billion per year and are the fastest growing application area for lasers. Laser scanners are just now

emerging and will provide data input for the paper-free office systems of the future, based on optical storage; they should enjoy a large market. Laser-based processes for manufacturing in diverse and giant industries, such as automobiles, chemicals, and semiconductors, will have major economic implications that are just now becoming evident.

Assuring U.S. competitiveness in lasers and laser-based products for commercial applications will require the development of new lasers with new capabilities, higher performance levels, improved quality, and reduced cost. All of these aims are highly measurement dependent. The measurement support required has outstripped the capabilities of NIST's small laser measurement program. In response, NIST has planned this new program which focuses on measurement methods for the performance and quality of lasers and laser optics. The expanded scope of this program will emphasize support for (1) additional specific measured quantities, (2) higher accuracies, (3) broader frequency ranges, and (4) broader power levels. NIST will also develop national reference standards as needed to support the measurement methods. NIST will develop new laser measurement services and standard reference materials as required; these will be provided to users on a reimbursable basis.

The new NIST measurement program will support: research and development toward new lasers; development of laser-based products; improved quality control during manufacturing of lasers and laser-based products; establishment of voluntary industry standards for compatibility and other aims; improved specification and procurement of lasers and laser-based products; and improved access of U.S. laser products to foreign markets. The beneficiaries will include U.S. industry, U.S. Government, and all developers, buyers, and users of lasers and laser-based products and services.

Organization of this document

Laser Light	}	tutorial on lasers
Principle of Laser Operation		
Types of Lasers		
World Market for Lasers and Laser Optics	}	information on market and U.S. competitiveness
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Appendix 1: Needed Versus Present NIST Capability		technical details

Laser Light

Light is electromagnetic radiation, much like radio waves, but light is much higher in frequency. Light travels in waves that are similar to waves of water moving across a pond. Waves of water exhibit alternating peaks and valleys as they pass by. Waves of light do, too, even though the peaks and valleys cannot be seen. The distance from one peak to the next is the "wavelength" of light. The number of peaks per unit time that passes a given point is the "frequency" of light. The frequency of light determines its color. The human eye can see only a narrow range of frequencies that vary about a factor of two from red at the low end to violet at the high end. Light of other frequencies, both higher and lower, exists, even though it is not visible.

The position of light in the frequency spectrum is shown in Table 1. Lasers can generate a wide range of frequencies. Some of those frequencies fall within the range of human vision, and others lie outside that range.

Table 1
Overview of Frequency Spectrum

Megahertz (MHz) = 10^6 Hz	medium frequency waves very high frequency waves ultra high frequency waves		AM radio FM radio, TV, etc. TV, other
Gigahertz (GHz) = 10^9 Hz	centimeter waves millimeter waves sub-millimeter waves	}	microwaves
Terahertz (THz) = 10^{12} Hz	far infrared light near infrared light <u>visible light</u>	}	LASER FREQUENCIES
Petahertz (PHz) = 10^{15} Hz	ultraviolet light x-rays	}	

In ordinary light, like that from the sun or light bulbs, many different lightwaves travel along together without any special relationship to each other. Some of the lightwaves are a bit ahead of, or behind, those along side them. Laser light, in its ideal form, is different for three reasons. First, laser light has one frequency, that is, one color. Second, all of the waves in laser light travel in a single direction. Third, all of the waves are in lock step with those along side them, like soldiers marching in perfectly aligned rows. These three characteristics of laser light (single color, single direction, lock step nature) constitute the property of "coherence". Coherence gives laser light these special capabilities:

- (1) It can be focused to a small point.
- (2) It can interact with materials selectively.
- (3) It can "interfere" with itself in special ways.

The first capability enables lasers to cut materials and to launch light into the very small core of an optical fiber. The second capability enables lasers to stimulate specific chemical reactions. The third capability enables lasers to detect small imperfections in the shapes of objects and to produce three-dimensional images suspended in air (holography).

Take cutting as an example. Because laser light can be focused to a small point, its energy can be highly concentrated. This concentration enables lasers to cut materials by ripping individual atoms from them (ablation). This process produces a particularly clean edge.¹

Principle of Laser Operation

All lasers rely on the same basic principle for operation. That principle is embodied in the word "laser" itself, which is an acronym for light amplification by stimulated emission of radiation. Inside a laser, energy is stored in a physical medium. The energy is released in a rush when a weak beam of light of a specific color passes through the medium. As the energy is released, it produces additional light of the same color. The additional light joins with the light in the weak beam, thus amplifying it.

The release of the additional light occurs in a coherent manner. This means that all of the peaks and valleys in the wave of the original weak beam are strengthened without being disturbed from their perfect regularity. Using the analogy to marching soldiers, this process is much like adding new soldiers to each row of soldiers marching by without disturbing the perfect straightness and spacing of the successive rows. Thus, in a laser, a weak beam of light is amplified into a strong one by the stimulated emission of additional light of exactly the same nature.

The laser medium is usually in the form of a rod, a tube, or a rectangular solid. Special mirrors are placed at opposite ends of the medium.² The mirrors reflect laser light back and forth through the medium. On each pass through the medium, the strength of the laser light is amplified by further stimulated emission. The mirror at one end is partially transparent to allow a portion of the laser light to be released continuously for use. Sometimes that mirror is blocked from the inside by a special material that can be "switched" from a transparent state to an opaque state. This special material enables the laser to be turned on and off so that it can produce pulses instead of continuous output. Outside a laser, other precision optical materials, such as additional mirrors and lenses, are used to direct the light and to condition it for specific applications.

Types of Lasers

There are several types of lasers. They can be classified by the "state" and the "structure" of the physical medium that stores energy in the laser. The "state" of the medium indicates whether it is a solid, a liquid, a gas, or a "gas" of free electrons in a beam in a vacuum. The "structure" of the medium indicates whether the "active part" of the medium (the part which produces the light) is composed of isolated atoms (atomic structure), chemically combined sets of atoms (molecular structure), periodic arrays of atoms (crystalline structure), or free electrons in a "gas" (electron gas). Table 2 shows the types of lasers and provides examples of specific lasers important to a wide variety of applications of lasers.

Table 2
Types of Lasers

<u>Medium</u>		<u>Subgroup</u>	<u>Examples</u>
<u>State</u>	<u>Structure</u>		
solid state	atomic	semiconductor diode	neodymium embedded in yttrium aluminum garnet ³
	crystalline		gallium aluminum arsenide
liquid state	molecular	dye	rhodamine G
gaseous state	atomic	non-ionic	helium neon helium cadmium
		ionic	argon
	molecular	common chemical excimer ⁴	carbon dioxide hydrogen fluoride argon fluoride
electron gas	electron gas		free electron

The frequency of a laser is determined by many factors. The laser medium is the most important. It determines the set of frequencies that the laser can potentially produce. The actual frequency produced by a laser is selected from this set by adjusting the positions and properties of the mirrors and the other optical components of the laser.

World Market for Lasers and Laser Optics

Comments about Market Data

Available world market data for lasers and laser-based products is spotty. World market data is available for lasers and for some laser-based products used in commercial applications. World market data is not generally available for lasers and laser-based products used in government applications. Available market data from different sources sometimes agree only to within a factor of two. Further, projections made just four or five years ago for laser-based products for commercial applications often understate the size of the present market.

All Optoelectronic Components

The world market for all optoelectronic components and systems, of which lasers are one part, is growing rapidly. That market is expected to increase from \$45 billion in 1988 to \$70 billion in 1995 and to \$103 billion in 2000.⁵

Lasers and Laser-Based Products

Well documented data on the present world market for lasers and laser-based products for both commercial and government applications is lacking; but the information available suggests that the market is already in excess of \$14 billion per year, and likely by a wide margin.⁶

Lasers

For lasers themselves, current data are available for the commercial component of the world market. Sales of lasers in this market have been estimated at \$720 million for 1989.⁷ "Commercial" lasers in this case include those sold for commercial applications only, except that all lasers sold to both commercial and government buyers for research and development are included.

Sales of lasers to the government component of the world market are more difficult to determine. However, if laser sales are assumed to divide between the commercial and the government sectors in the same proportions as the combined sales of lasers, laser equipment, and laser services, then the total world market for lasers can be estimated at \$1.9 billion for 1989. This amount may be an overestimate since it is based on commercial/government fractions for 1985, before the commercial market had developed to the extent that it has now.⁸

The growth rate for the world market for commercial lasers is estimated at 14% from 1988 to 1989 in terms of current dollars (inclusive of inflation).⁹ The growth rate for unit sales of lasers from 1988 to 1989 is estimated at 32%.¹⁰ The high growth rate in unit sales reflects the rapid and broad adoption of lasers as components in other products. The smaller growth rate in dollar value reflects the emergence of low-priced lasers and the intense price competition in the marketplace.

Laser Optics

The most important components supporting the use of lasers are laser optics. Laser optics include lenses, mirrors, prisms, windows, filters, gratings, beam splitters, polarizers, and other components that are used within and outside lasers. Laser optics create, condition, and direct laser beams. Laser optics constitute "anywhere from 10 to 15% of the contents" of lasers.¹¹

U.S. production of laser optics for both government and commercial applications is projected at \$176 million for 1989, an increase of 8% over 1988 in current dollars.¹² A figure for the world market is lacking but can be estimated from the 1988 U.S. share of world production, 45%,¹³ if that share is assumed unchanged for 1989. Such a share would imply a world market of about \$391 million for 1989. An estimated \$300 million of this amount is for external optics (optics used outside lasers as opposed to the internal optics built into lasers).¹⁴ The remaining \$91 million is for internal optics and therefore is already reflected in the \$1.9 billion figure for the world laser market. Thus, the combined world market for lasers and supporting external optics is about \$2.2 billion per year (= \$1.9 billion + \$0.3 billion).

U.S. International Competitiveness

As noted above, the world market for all optoelectronic components and systems is presently \$45 billion. This market is dominated by Japan, which controls about 51% of it.¹⁵

Lasers

U.S. consumption of lasers is projected at 38% of the world's production for 1989.¹⁶ U.S. production of lasers, as a percentage of world production, has been falling rapidly, as shown in Table 3. In the five years from 1982 to 1987, the U.S. lost half of its market share to Japan and Europe.

Table 3
World Market Shares of Production (percent)¹⁷

	<u>U.S.</u>	<u>Japan</u>	<u>Europe</u>	<u>Other</u>
1982	75	10	10	5
1987	38	27	30	5

Japan's success is attributed to its efforts to develop its domestic market first, to reduce costs and refine its products, and then to enter foreign markets with low-priced exports.¹⁸ Japan appears committed to maintaining its excellence in laser technology. A portion of a recent \$1.6 billion Japanese program for funding basic and applied technologies has been focused on lasers and electro-optics.¹⁹ The seriousness of the Japanese challenge was recognized in 1985 in the DOC-sponsored Japanese Technology Evaluation Program (JTECH) which found that the gap between Japan and the U.S. for the technology underlying semiconductor lasers was threatening to become permanent.²⁰ Comments on Japan's competitiveness in specific laser applications have been incorporated into the section "World Commercial Market by Laser Application" that follows.

Europe, too, is emphasizing laser research and the development of laser applications in its long-range plans. Through the European Economic Community, Europe is investing \$400 million over the next five years in this field.²¹ Europe is expected to have increasing success in penetrating the U.S. market for industrial lasers; U.S. consumption of European industrial lasers is expected to increase 9% per year through 1994.²²

Many changes, both technical and non-technical, are deemed necessary to restore U.S. competitiveness. Included among the technical changes are improved quality, reliability, and manufacturing excellence for U.S. laser products. In particular, the U.S. must invest "in the engineering of manufacturing systems that are competitive with the Japanese."²³ All of the required technical improvements are highly measurement dependent.

Laser Optics

In the closely related field of laser optics, U.S. competitiveness has also been dropping rapidly. In 1984 the U.S. made 63.5% of high-technology laser optics. By 1988 the U.S. share had

dropped to 45%. Again, quality control is cited as one of the key factors explaining the loss of U.S. competitiveness.²⁴

The loss of U.S. competitiveness is not limited to the commercial market. The military part of the government market is also affected. A key indication of this effect is that the U.S. military is turning to foreign suppliers, reluctantly but increasingly, for the electro-optic products that it needs.²⁵ In fact, the DOD is purchasing about half of all its optical components (laser-related and other) from foreign suppliers. The situation is regarded as so critical that a Federal Acquisition Regulation is under consideration; it would require that DOD purchase all of its precision optical components from domestic manufacturers. The purpose of the regulation is "to help restore the depleted optics manufacturing base and provide a reliable domestic source of components for the national defense."²⁶

World Commercial Market by Laser Type

The dominant types of lasers in the world commercial market are shown in Table 4. In some cases individual lasers are shown, such as carbon dioxide lasers. In other cases, a whole category of lasers, such as dye lasers, is shown, in keeping with the practices of categorization common in the industry. The lasers are arranged in order of sales from the highest to the lowest in dollar value. The dollars and percentages reflect current dollars (inclusive of inflation). The first four types of lasers account for 82% of the world commercial market on a dollar basis: semiconductor diode, carbon dioxide, ion, and yttrium aluminum garnet.

Table 4
1989 World Commercial Laser Sales (Dollars) by Laser Type²⁷

	<u>Sales (\$Million)</u>	<u>Percent</u>	<u>Percent Growth</u> <u>1988 to 1989</u>
semiconductor diode	211	29	17
carbon dioxide	137	19	11
ion	124.4	17	13
yttrium aluminum garnet	122.4	17	9
helium neon	56.2	8	10
excimer	26.9	4	13
dye	22.6	3	10
helium cadmium	19.4	3	54
	<u>720</u>	<u>100</u>	<u>14</u>

Unit sales of lasers in the world commercial market are shown in Table 5. Unit sales are heavily weighted toward the two lowest cost lasers: the semiconductor diode lasers and the helium neon lasers. In fact, 98.4% of the estimated 25,080,400 lasers that will be sold in the world commercial market in 1989 will be semiconductor diode lasers even though they account for 29% of the market on a dollar basis.

Table 5
1989 World Commercial Laser Sales (Units) by Laser Type²⁸

	<u>Units</u>	<u>Percent</u>
semiconductor diode	24,690,000	98.44
helium neon	360,900	1.44
all others	29,500	0.12
	25,080,400	100.00

The reduction of the semiconductor diode laser to a commodity is one of the most important developments in laser technology in this decade. Nowhere is the impact of this development more evident than in the product category of optical memories, which now uses 74% of all laser units sold in the commercial market.²⁹ Although the U.S. invented the semiconductor diode laser, Japan was the first to reduce it to a cheap product (less than \$10); and Japan now virtually owns the consumer market for the resulting products, such as the audio compact disk players.³⁰

The growth of the market for semiconductor diode lasers has been further accelerated by the emergence of (1) higher power diode arrays that produce watts of output versus milliwatts³¹, (2) visible diode lasers to complement earlier infrared versions³², and (3) electronically steerable versions. These developments have greatly broadened the potential applications of semiconductor diode lasers.

It is noteworthy that semiconductor diode lasers have begun substituting for helium neon lasers in many applications, reducing product cost and broadening markets accordingly. Also, diode lasers have become integral components in other types of lasers, particularly in "atomic" solid-state lasers. In the resulting "hybrid lasers", the diode lasers "charge up" or "pump" the active atomic element in the medium of an atomic solid-state laser (usually neodymium in yttrium aluminum garnet). The atomic solid-state medium then produces the light output of the laser. Relative to diode lasers themselves, this hybrid laser provides a greater diversity of frequencies and a pulsed output at a higher peak power level. Compared to alternative lasers, the hybrid lasers offer high efficiency, small size, stable low-noise output, and desirable optical properties.³³ Thus diode lasers are improving the utility, reducing the cost, and broadening the applicability of other types of lasers, too.

World Commercial Market by Laser Application³⁴

The applications of lasers sold in the commercial market are diverse and expanding. Lasers applications can be divided into two classes that serve four basic functions, as shown in Table 6.

Table 6
Classes of Laser Applications

<u>Classes</u>	<u>Functions</u>	<u>Examples</u>
Energy	deliver energy	surgery, welding, drilling
Information	read information	compact disk players, barcode readers
	generate information	medical diagnostics, environmental sensing
	transmit information	optical fiber communications, free-space laser communications

The dominant applications are listed in Table 7 in descending order of dollar sales of lasers to support the applications. The percentages of the world commercial market represented by the dollar sales are also shown, as are the percentages of growth in dollar sales anticipated from 1988 to 1989. All figures reflect current dollars. Laser sales for all but two of the applications are showing "healthy" to "extremely strong" growth rates. Even the one area that is decreasing in dollar sales, lasers for printers, is rising in terms of unit sales.

Table 7
1989 World Commercial Laser Sales (Dollars) by Application³⁵

	<u>Sales (\$Million)</u>	<u>Percent</u>	<u>Percent Growth 1988 to 1989</u>
Materials Processing	166	23	13
Research and Development	159	22	12
Medicine	113 ³⁶	16	10
Communications	76	11	8
Optical Memories	71	10	33
Printers	45	6	-3
Test and Measurement	35	5	23
Barcode Scanners	29	4	56
Color Separation	11	2	6
Entertainment	8	1	1
Alignment and Control	7	1	17
Total	<u>720</u>	<u>101</u> ³⁷	

As shown in Table 8, just four of the applications account for 99% of the estimated 25,080,400 lasers that will be sold in the world commercial market in 1989. For one of the applications, barcode scanners, semiconductor diode lasers are just now overtaking helium neon lasers in frequency of use. For the other three applications, semiconductor diode lasers totally dominate.

Table 8
1989 World Commercial Laser Sales (Units) by Application³⁸

	<u>Units</u>	<u>Percent</u>
Optical Memories	18,620,350	74
Printers	5,545,600	22
Barcode Scanners	525,000	2
Communications	234,300	1
	24,925,250	99

Here are examples of present and emerging uses of lasers in commercial applications. The applications are arranged in the same order as in the dollar-sales list in Table 7, that is, in decreasing order of dollar sales of lasers that support those applications.

Materials Processing

Lasers are presently used in (1) semiconductor processing, (2) materials working, and (3) marking.

Semiconductor processing

Semiconductor processing applications include lithography,³⁹ selective annealing, thin-film removal (resistor trimming), link-making and link-blowing on memory chips, vapor deposition, metal planarization, doping, hole drilling, surface inspection, etching, aligning, and photomask and screen generation, among others.⁴⁰

Materials working

Materials working applications include cutting, drilling, welding, and soldering. Lasers perform these tasks without contact with the material being processed and thus with no wearing of the "tool".⁴¹ Lasers can cut cleanly with virtually no damage to surrounding material; the ablative process that they employ circumvents the drawbacks of thermal processes such as melting or vaporization.⁴²

Japan has moved quickly to exploit the capabilities of lasers for manufacturing processes and reportedly has five times more laser cutters in service than the U.S. Further, the Japanese auto industry is eyeing laser welders to improve efficiency. Japan generally is aggressively pursuing industrial applications of lasers.⁴³

Europe, too, is targeting laser research for industrial applications through its Eureka Project.⁴⁴ At least one German automotive manufacturer (Volkswagen AG) has already implemented laser cutters in its automotive assembly operations.⁴⁵ Both the European nations and the U.S. also looking to laser welders for their auto industries.⁴⁶

Marking

Laser marking is applied to a broad range of products including pharmaceuticals, foods, cosmetics, circuit boards, automobiles, and many others. Laser marking is accomplished by ablating the surface layer of a material or by causing a color change in the surface layer through heating.

Laser marking has a long list of advantages over conventional methods of marking. Here are some examples: all materials can be marked; permanent, high quality marks can be produced; high resolution can be obtained; the marks can be made without contact, mechanical distortion, or contamination; and the marks can be made with high speed, low cost, and low maintenance.⁴⁷

While laser marking is presently a small area, it is rapidly expanding. In 1987, U.S. sales of laser marking systems were \$25 million to \$30 million. Fifty U.S. companies are already manufacturing marking systems.⁴⁸

Emerging applications

Other applications of lasers, related to manufacturing, are emerging. They include: stereo lithography (creation of three-dimensional solid parts from liquid photopolymers without cutting or molds)⁴⁹; surface treatments (hardening, alloying, glazing, annealing); scribing (for ceramics and glasses); laser-illuminated vision for robots, for positioning, and for inspection for quality control inspection⁵⁰; micromachining; and laser chemistry.

The micromachining capabilities of lasers are noteworthy. Lasers can easily operate on micrometer scales.⁵¹ For example, they can drill tiny holes through objects as small as human hairs.

The potential of lasers for laser chemistry is also very important. Laser light of the proper frequency can stimulate chemical processes that would not otherwise occur or that would occur too slowly to be commercially viable.

Research and Development

Virtually every field of research uses lasers: physics, photochemistry, materials science, electronics, biology, medicine, spectroscopy, laser fusion, and many others. In fact, the use of lasers in research and development is one indicator of the level of activity and health of a nation's research efforts.

The U.S. share of world laser consumption for research is dropping as other countries develop their research capabilities. In 1986, the U.S. accounted for about 45% of the world market for research lasers, Europe for 40%, and Japan and the Pacific Rim countries for about 15%. In 1988, only two years later, Europe surpassed the U.S. and accounted for 44% of the world market; the U.S. share dropped to 40%, and Japan and the Pacific Rim countries rose to 16%. Further reductions in the U.S. share are anticipated.⁵²

Medicine

The medical market for lasers is vast and growing. Both therapeutic and diagnostic applications are involved.⁵³

Diagnostic applications

Diagnostic applications include DNA sequencing, cell separation, cell sorting (cytometry), AIDS detection, cancer detection, and others.

Therapeutic applications

Therapeutic applications of lasers are wide ranging. Laser techniques are attractive because they are less invasive than other techniques. Therefore, they are easier on patients, and they can shorten hospital stays. In fact, of the 11.5 million surgical procedures performed each year in the U.S., an estimated 10% to 40% could potentially employ lasers.⁵⁴ Promising fields of medicine for increased use of lasers are shown in Table 9. The fields are listed in descending order of the number of locations already using lasers for those fields.⁵⁵

Table 9
Therapeutic Applications in Medicine

<u>Field of Medicine</u>	<u>Examples of Applications</u>
ophthalmology	radical keratotomy (nearsightedness correction), corneal sculpting (near- and farsightedness correction) ⁵⁶
obstetrics	
otolaryngology	
podiatry	
gastroenterology	
dermatology	
general surgery	
orthopedics	
plastic surgery	
urology	lithotripsy (kidney stone shattering)
cardiovascular surgery	heart treatment, photocoagulation, laser angioplasty (vaporization of fatty deposits and plaque in arteries)
colorectal surgery	
thoracic surgery	
neurology	neurosurgery
oncology	photodynamic therapy for removing cancers
gynecology	

The economic implications of the successful implementation of laser-based therapeutic procedures are highly significant. For example, corneal sculpting alone is estimated to have a potential market of \$6 billion per year for the replacement of eye glasses.⁵⁷

The combining of diagnostic and therapeutic functions in individual laser systems is particularly promising for the medical systems of the future. For example, in laser angioplasty, lasers can potentially be used to identify the material that is to be vaporized, to vaporize it, and to monitor the progress of the vaporization -- all in one combined process.

Communications

Applications of lasers in both optical fiber communications and free-space communications are important.

Optical fibers

Low frequency (near infrared) semiconductor diode lasers are the light sources for optical fiber communications systems, particularly for long distance systems, both cross country and undersea. A spokesman for a major Japanese company indicates that the U.S. market for these diodes will reach \$1 billion in the 1990s.⁵⁸

Free space

Laser communication systems for use in free space, air, or water are emerging. Lasers can potentially link: spacecraft (including satellites) to other spacecraft; spacecraft to aircraft; spacecraft to ground⁵⁹; and spacecraft, aircraft, and surface vessels to submarines⁶⁰. Such laser communication systems have several advantages compared to radio frequency systems: small size and weight; high information capacity due to the high frequency of operation; and high security and high freedom from interference due to narrow beam divergence.⁶¹ These advantages must be weighed against the disadvantages: greater weather sensitivity when penetrating the atmosphere, and higher requirements for pointing accuracy due to the very narrow beams.

Optical Memories

Optical memories are the second fastest growing application of lasers and presently consume 74% of all laser units sold for commercial applications.⁶² Optical memories include audio compact disk (CD) players, video players, and optical data storage devices for computers. In 1988, Japan produced \$6.6 billion of optical disk products of all types, including read-only and read-write (erasable) systems for audio, video, or data storage. The read-write systems are just now emerging. Japan produced \$121 million of the read-write optical products in 1988.⁶³ Worldwide shipments of optical disks alone will increase in value from \$3.9 billion in 1989 to \$10 billion in 1993.⁶⁴

Compact disk audio players and video players

For compact disk audio players, which are a read-only technology, Japan presently holds a 90% share of world production.⁶⁵ The U.S. is one of the major consumers of these products. In 1988, 5 million units with an estimated factory-to-dealer sale value of \$1 billion, were sold in the U.S. The U.S. market for the players is expected to grow 20% in 1989.⁶⁶ The players were introduced in 1982, and since that time 11% of U.S. households have acquired a player.⁶⁷

Data are not available for video players, but sales are believed to be much smaller. Players combining video capability with compact disk audio capability are now available.

Optical data storage devices

For optical data storage devices, including both read-only and read-write implementations, present and projected growth rates are very high. The world market is expected to increase ten fold in just four years from \$2.0 billion in 1988 to \$21.5 billion in 1992. At that time, optical data storage is expected to account for 25% of the market for all forms of data storage.⁶⁸

The U.S. is already a major consumer of this new technology. In 1988, the U.S. represented 73% of the world market for optical data storage products. In 1993, the U.S. is expected to represent 60% of the world market.⁶⁹

Optical data storage systems offer the highest information density per unit area yet achieved. However, compared to magnetic storage systems, the optical systems presently have slower access times; and, in read-write formats, they are less reliable for long-term data storage. Optical systems have also not been implemented in a tape format which provides must greater area for storage than a disk format. Optical technology will have to compete with continued advances in magnetic technology.

Compact disk read-only memories (so-called CD-ROMs) were the first optical data storage products. As their name suggests, they can be read from but not written to, so they can handle only permanently recorded data. As of the end of 1987, CD-ROMs had found use primarily in library, financial, and medical areas. During 1988 additional users emerged in the Federal Government (including the military) and in legal and religious communities. In 1989 further markets are expected to surface in "architecture and construction, aerospace and airline industries, electronic design engineering, travel & leisure, space and planetary science, and maybe even education".⁷⁰ The world market for CD-ROM drives for 1989 is estimated at 179,200 drives, valued at \$108 million. The world market is expected to rise to 691,600 drives in 1993, valued at \$0.2 billion to \$0.4 billion.⁷¹

Laser Printers

Laser printers are being adopted widely, with annual sales of \$3 billion in 1988, an increase of 28% over the previous year. However, the growth in sales is slowing, and the average unit cost of the lasers they contain is dropping. These factors have lead to a projected decrease

in total dollar volume of laser sales from 1988 to 1989.⁷² Japan presently holds an 85% share of world production of low-end laser printers.⁷³

A related emerging application is laser scanning. Laser scanners are capable of digitizing virtually any image. Present scanning speeds are approaching 10 megapixels per second.⁷⁴ The scanners are essential to new filing systems based on optical data storage. These systems completely replace paper copy and yet produce high quality paper output on demand. While estimates of the potential markets for such filing systems are not yet available, those markets will be vast.

Test and Measurement

Test and measurement applications are diverse and include: measurement of particles; environmental sensing; measurement of thickness of and voids in plastics; measurement of surface finish and distortions of many types, including those in aircraft tires; and other applications.

The opportunities in environmental sensing have significant economic potential. The capabilities of two types of laser systems are presently being tested: laser radar (lidar)⁷⁵, and laser-induced fluorescence. Laser radar can be used to detect atmospheric pollutants, such as ozone⁷⁶ and aerosols,⁷⁷ or weather-related parameters, such as water-vapor concentration and wind velocity.⁷⁸ Laser radar conducted from aircraft can be used for estimating tree height and timber yield, and for biomass estimation more broadly.⁷⁹ Laser-induced fluorescence, generally conducted from aircraft, is also a powerful technique. Plants are illuminated from aircraft with a pulsed laser. In response they fluoresce (emit light). Analysis of the fluorescent light enables identification of plants and assessment of plant vigor. In particular, the analysis can provide information on drought effects, nutrient deficiencies, acid-rain effects, fungal infestations, abnormal levels of heavy metals,⁸⁰ and, possibly, presence of herbicides.⁸¹

Barcode Scanners

Barcode scanners have penetrated supermarkets but have only begun to penetrate other retail outlets, warehouses, and industrial and medical locations. Nevertheless, barcode scanners already represent a \$2.5 billion per year industry.⁸² They are the fastest growing application for lasers.

Color Separation

Lasers are used to separate the colors during color printing. They are also used increasingly to make the plates used for printing.

Entertainment

Entertainment applications include light shows and laser pointers. These applications are likely to remain slow in growth due to stringent safety regulations, particularly in the U.S.⁸³

Alignment and Control

Alignment and control applications include surveying, construction alignment, tool alignment, agricultural applications (e.g., laser guidance for leveling of fields), and many others.

Other Emerging Laser Applications

Other applications of lasers are emerging, as shown in Table 10. Laser radar (lidar) systems have potential for improving aircraft and automobile safety. Lidar systems, like their microwave counterpart, radar systems, are under evaluation for aircraft and automobile collision avoidance and for wind-shear detection.⁸⁴ Lasers also offer potential for projection displays.

Table 10
Other Emerging Laser Applications

safety	automobile anti-collision aircraft anti-collision aircraft wind-shear detection ⁸⁵
displays	heads up instrumentation displays projection television

Types of Lasers Employed in Commercial Applications

A wide variety of types of lasers are presently employed in commercial applications, as shown in Table 11. The applications are again listed in descending order of anticipated dollar sales of lasers in 1989. For each application, the lasers themselves are listed in descending order of dollar sales. The unit-sales order would differ. For example, semiconductor diode lasers and helium neon lasers are less expensive than other types of lasers, so on a unit-sales basis they would move closer to the beginning of the lists for individual applications.

Table 11
Types of Lasers Employed in Commercial Applications⁸⁶

<u>Application</u>	<u>Types of Lasers Employed</u>
Material Processing	carbon dioxide, yttrium aluminum garnet, excimer, helium cadmium, ion
Research and Development	ion, yttrium aluminum garnet, excimer, semiconductor diode, dye, carbon dioxide, helium neon, helium cadmium
Medicine	ion, yttrium aluminum garnet, carbon dioxide, dye, helium neon, excimer
Communications	semiconductor diode
Optical Memories	semiconductor diode
Printers	semiconductor diode, helium neon, ion
Test and Measurement	semiconductor diode, helium neon, ion, yttrium aluminum garnet, helium cadmium
Barcode Scanners	helium neon, semiconductor diode
Color Separation	ion, helium neon
Entertainment	ion, helium neon
Alignment and Control	helium cadmium, helium neon, semiconductor diode

Note that two types of lasers introduced earlier are not significant in the commercial market: chemical lasers and free electron lasers. These lasers are capable of very high output and have other special properties. They are important primarily to research activities and to military applications.

Government Applications of Lasers

Government applications include nearly all commercial applications and others as well. Applications especially significant to the U.S. military are shown in Table 12.

Table 12
U.S. Military Applications of Lasers

- Research and Development
- Targeting and Ranging
- Directed Energy Weapons
- Communications
- Guidance (laser gyros)

Current data on the world market for government applications of lasers are lacking. However, in a 1986 study, a projection of \$3.9 billion was made for the 1989 "shipments" for U.S. military laser equipment and research.⁸⁷ A breakdown by category is shown in Table 13. The application representing more dollar investment than any other in each category is shown as the "principal application". Other applications are also important to each category shown.

Table 13
Projected 1989 "Shipments" for U.S. Military Laser Equipment and Research

<u>Category</u>	<u>Principal Application</u>	<u>\$Million (1989)</u>
Aircraft Programs	targeting and ranging	1098
Space Armament Research	directed energy weapons	912
Missile Programs	targeting and ranging	902
Battlefield Programs	targeting and ranging	708
General Laser Research	research and development	237
Communication & Shipboard Programs	targeting and ranging	45
Total		<u>3,902</u>

The laser content of these shipments is not known, but it is likely a relatively small fraction of the total (probably less than one-fourth) since the study indicates: "In all categories, the value of the complete identifiable system has been used, not just the laser as a component."⁸⁸

U.S. Industry's Technical Goals for Improved Competition

U.S. industry must pursue three major goals to improve the competitiveness of its laser products:

- (1) Develop new lasers with additional capabilities and higher performance levels, specifically:
 - more frequencies
 - higher power levels
 - improved beam quality
- (2) Improve quality control during manufacturing
- (3) Reduce product cost

In addition, U.S. industry must apply laser technology more effectively in multiple areas of laser-based products and processes to maintain its competitiveness in those areas.

All of these goals are highly measurement intensive.

NIST Measurement Support for Industry's Technical Goals

To support industry in pursuit of its goals, NIST has developed this plan for a new program of measurement support. NIST will undertake two projects for the development of new measurement capability:

- Project 1. Laser Performance and Quality Measurements
- Project 2. Laser Optics Performance and Quality Measurements

Project 1 will focus on measurements of the key quantities that determine overall laser performance and quality. Project 2 will focus on measurements of the key quantities that determine the performance and quality of the laser optics that are used within and outside lasers to create, condition, and direct laser light. Detailed descriptions of the two projects, focusing on the specific measurement methods to be developed, are provided in the next two sections. The projects are listed in the order in which they will be funded if the additional resources required can be obtained.

Both projects support industry in its pursuit of the three goals required for increased competitiveness in laser products. Both also support industry in developing products and processes that employ lasers.

The principal improvements needed in the scope of NIST measurement capability are shown below.

Table 14
Scope of Needed NIST Measurement Capability

additional specific measured quantities	support for all key measured quantities required for characterization of modern lasers, versus the few now supported
higher accuracies	ten to twenty times present accuracies for the few measured quantities presently supported, and very high accuracies for additional measured quantities
broader frequency ranges	support for all measured quantities over broader ranges of frequencies, versus the limited ranges now supported
broader power levels	support for all measured quantities over broader power levels, versus the limited levels now supported

The additional quantities that require measurement support were identified based on information from industry, from other Federal agencies, and from the National Conference of Standards Laboratories (NCSL), composed of industry and Government-agency representatives. The NCSL surveyed over 400 organizations within the U.S., including 346 industrial companies, 61 government agencies, and 4 universities, to determine the critical measurement needs in the many technologies that NIST must address to serve "national interests including commerce, international competitiveness, and defense preparedness."⁸⁹

NIST will address the measurement needs of all commercially important types of lasers. However, a special emphasis will be placed on semiconductor diode lasers. They are the most important lasers in the commercial market on both a dollar volume and a unit volume basis. They are effective in commercial applications for several reasons: they are small in size and low in cost relative to all other types of lasers; they are being made in new forms that produce additional frequencies needed by many applications; they are yielding ever higher

powers levels; and they are proving useful in concert with other types of lasers in hybrid ("diode-pumped") lasers that provide even more frequencies and even higher power levels for pulsed output. Measurement support needed for laser diodes for a broad range of applications is discussed here. However, measurement development needed especially for low frequency (near infrared) laser diodes for optical fiber communications will be carried out in a new program focused on that application. That program is described in Chapter 5.

Project 1. Laser Performance and Quality Measurements

NIST will develop measurement methods for characterizing the performance and quality of lasers. The measurement methods needed fall into two principal categories: beam strength measurements and beam quality measurements. Both types of measurements are essential for the development of lasers and laser applications. Beam quality measurements are necessary because all laser beams depart from ideal behavior. Those departures must be measured and minimized to the degree necessary for the success of lasers in a given application. The measured quantities of interest are shown in Table 15.

Table 15
Laser Performance and Quality Measurements

<u>Measured Quantity</u>	<u>Description</u>
beam strength measurements	
average power	power output from a continuous-wave laser
pulse energy	energy output from a pulsed laser
peak power	highest instantaneous output occurring during a pulse from a pulsed laser
beam quality measurements	
temporal	
continuous-wave lasers	
frequency stability	stability of frequency over time ⁹⁰
power stability	stability of power over time
pulsed lasers	
pulse shape	evolution of pulse strength with time
pulse stability	for successive pulses over time:
timing	stability of timing
energy	stability of energy per pulse
peak power	stability of peak power per pulse
frequency	stability of frequency
switching speed	speed at which laser can be turned on and off (for laser diodes) ⁹¹

Table 15 (continued)
Laser Performance and Quality Measurements

<u>Measured Quantity</u>	<u>Description</u>
beam quality measurements	
spatial	
beam divergence	angular width of beam
beam profile	power distribution across face of beam
beam direction	direction of beam (for steerable laser diodes)
modal	
power in modes	distribution of laser power among complicated internal modes of laser operation
polarization	
angle	angular direction of polarization of laser beam
purity	degree to which polarization of laser beam points in a single direction
coherence	
temporal	degree to which laser beam is truly coherent over time
spatial	degree to which laser beam is truly coherent across the front of the beam
phase front	uniformity of phase across front of beam (for laser diode arrays)
noise	
phase noise	unwanted variations in the laser beam fluctuations in timing of instantaneous power of beam
amplitude noise	fluctuations in instantaneous power of beam
bulk noise	fluctuations in average power of beam
photon statistics	distribution of photons in time ⁹²
spectral	
purity (linewidth) ⁹³	degree to which laser beam is truly a single color (single frequency)

Three of the measured quantities above apply especially to diode lasers: switching speed for ultra high speed data and communications applications; beam direction for new electronically steerable diode lasers; and phase front measurements for powerful new diode laser arrays.⁹⁴ The other measured quantities apply to lasers broadly.

For any given application a large number of these measured quantities will be important. Here are examples of some of the quantities important to selected applications.

Materials processing: Lasers used for cutting, drilling, and welding depend critically on precisely measured levels of beam strength. Further, beam strength must be measured at many different frequencies, since different frequencies will be needed to interact optimally with different materials. For example, for cutting many materials, very high frequency lasers (ultra violet) are often the best choice. Also important is the measurement of the power in the various modes of the lasers, since minimizing the power in unwanted modes is essential to focusing the beam to a sharp point. Temporal measurements are critical to all applications of pulsed lasers used for materials processing.

Medicine: Lasers used for surgery must have precisely known levels of beam strength and beam profile. For example, the promise of corneal sculpting for replacing eye glasses cannot be realized without accurate beam profile measurements to determine the exact distribution of laser energy across the beam and thus across the cornea. Surgical applications, broadly, require lasers that operate at many different frequencies to permit selection of frequencies that provide strong interaction with the tissue to be removed but minimal interaction with the tissue to be retained. Measurement of the temporal properties of lasers is very important to medicine since pulsed lasers are frequently used for surgical processes.

Communications: For laser communications, switching speed and spectral purity (linewidth) measurements are important to the most powerful implementations, whether in optical fiber systems or in free-space applications. Also important is the measurement and minimization of noise on the beam which can interfere with the transmission of data.⁹⁵

Test and Measurement: Measurements of coherence are particularly important to precise test and measurement processes, such as inspection of surface irregularities.

In addition to developing measurement methods for the quantities in Table 15, NIST will develop national reference standards needed to support those measurement methods. NIST will also develop measurement services and standard reference materials for quantities requiring them, and will provide both to users on a reimbursable basis. Heavy use of the services is anticipated by both manufacturers of lasers and manufacturers of laser-based products.

Project 2. Laser Optics Performance and Quality Measurements

Laser optics include lenses, mirrors, prisms, gratings, windows, filters, beam splitters, and other components that are used within and outside lasers to create, condition, and control the direction of laser beams. The performance and quality of laser optics have a controlling effect on the quality of the light produced by a laser. Special measurement methods are required to improve the design of laser optics and to control their quality during manufacturing. New or improved measurement methods will be needed for the quantities shown in Table 16.

In addition to developing measurement methods for the quantities in Table 16, NIST will develop reference data on the properties of laser optic materials, using the measurement methods that it develops. This reference data will support both the design of improved laser optic products and the control of quality during their manufacture. NIST will also develop measurement services and supporting standard reference materials (SRMs) for the quantities requiring them. NIST will provide these services and SRMs to users on a reimbursable basis.

While carrying out the above two projects, NIST will evaluate evolving industrial needs for special measurement methods, and possibly SRMs, for "worked" materials, that is, for the materials that lasers cut, drill, weld, etc. Additional measurement development may be needed for those materials in order to support key applications of lasers, particularly in manufacturing.

Table 16
Laser Optics Performance and Quality Measurements

<u>Measured Quantity</u>	<u>Description</u>
transmission properties	
scattering	deflection of light in an optical component by imperfections
reflectivity	amount of light reflected by an optical component instead of transmitted through it
absorption	amount of light absorbed per unit volume of an optical material
attenuation	reduction in strength of a light beam after passing through an optical component
damage threshold	beam strength measurements for determining minimum power per unit area ("irradiance") and minimum energy per unit area ("fluence") that will damage optical components
refractive index ⁹⁶	degree to which light beam is slowed down as it passes through an optical material
birefringence	difference in refractive index for light of different polarizations passing through an optical material
magneto-optic properties ⁹⁷	optical properties controlled by magnetic fields
electro-optic properties	optical properties controlled by electric fields
non-linearities	departures of optical materials from linear (or proportional) response to light
imaging quality	degree to which optical components direct light as designed (requires new definitions appropriate for coherent systems) ⁹⁸

Appendix 1
NEEDED VERSUS PRESENT NIST CAPABILITY

Industry needs broader frequency coverage for all measured quantities required to support laser performance and quality measurements. The needs are already urgent in the segments of the frequency spectrum marked "first" and "second" priority in Table 17. The needs in the segment marked "third" priority are just now emerging. NIST's present capability does not cover even the first priority frequencies for the few measured quantities that NIST does now support.

Table 17
Industry's Frequency/Wavelength Priorities

	<u>Frequency</u>	<u>Wavelength</u>	<u>Priority</u>
submillimeter & far infrared	300 gigahertz	1 millimeter	] second
near infrared	30 terahertz	10 micrometers	
visible	430 terahertz	700 nanometers	] first
	750 terahertz	400 nanometers	
ultraviolet	2 petahertz	180 nanometers	] third
	30 petahertz	10 nanometers	

Notes: gigahertz = 10^9 hertz millimeter = 10^{-3} meter
 terahertz = 10^{12} hertz micrometer = 10^{-6} meter
 petahertz = 10^{15} hertz nanometer = 10^{-9} meter

The boundaries of the near infrared and the far infrared regions of the frequency spectrum are not rigorously defined. In Table 17, the term "near infrared" is used to refer to the region from 700 nanometers to 10 micrometers. Sometimes "near infrared" is used to refer to the more limited region of 700 nanometers to 2.5 micrometers; in such cases, the term "intermediate infrared" is used to refer to the region from 2.5 to 10 micrometers.

Long wavelengths (down to 1 millimeter) are useful for weather detection, spectroscopy, terrain following radar, and surveillance.

The following tables show how the accuracy and wavelength coverage of NIST's present measurement capability compares with industry's requirements. The tables are arranged under the project titles used earlier to describe NIST's plan for a new program.

Project 1. Laser Performance and Quality Measurements

Beam Strength Measurements

NIST's present program provides limited measurement support at selected wavelengths for all three quantities important to beam strength measurements: average power, pulse energy, and peak power. Table 18 addresses average power. The first column in the table shows the power levels of interest to industry. The second column shows the measurement accuracy that industry needs at each power level. The third column shows the power levels for which NIST presently provides measurement support and the accuracy that NIST provides at each level. Thus NIST provides some measurement support from 1 microwatt to 300 watts but no measurement support below 1 microwatt or above 300 watts. The fourth column shows the improvements that NIST can make in its present capability with present resources, that is without the new program described here. Further coverage will require the new program. Tables 19 and 20 provide similar information for pulse energy and peak power, respectively.

Table 18
Average Power

<u>Average Power</u>	<u>Estimated Accuracy Needed by Industry</u>	<u>Present NIST Capability accuracy / wavelengths</u>	<u>Improvement Achievable Without New Program accuracy / wavelengths</u>
1 nanowatt	0.1%	1.0% — visible, near IR, no far IR, no UV 2.0% 10.6 micrometers	0.6% — visible, near IR, no far IR, no UV 1.5% 10.6 micrometers
1 microwatt			
1 watt			
300 watts			
1 kilowatt			
50 kilowatts	2%		
> 1 megawatt	5%		

Notes: nanowatt = 10^{-9} watt
microwatt = 10^{-6} watt

kilowatt = 10^3 watts
megawatt = 10^6 watts

IR = infrared
UV = ultraviolet

Table 19
Pulse Energy

<u>Pulse Energy</u>	<u>Estimated Accuracy Needed by Industry</u>	<u>Present NIST Capability accuracy / wavelengths</u>		<u>Improvement Achievable Without New Program accuracy / wavelengths</u>			
10 attojoules	5%						
1 femtojoule	5%	] 10%	1.06 micrometers	6%	1.06 micrometers	
100 nanojoules	1%			10%	1.06 micrometers		
10 millijoules	0.1%	] 1.5%	1.06 micrometers	1%	1.06 micrometers	
100 millijoules	0.1%] 10%	10.6 micrometers	5%	10.6 micrometers
300 millijoules	0.1%						
1 joule	0.1%						
1 kilojoule	5%						

Notes: attojoule = 10^{-18} joule millijoule = 10^{-3} joule
 femtojoule = 10^{-15} joule kilojoule = 10^3 joule
 nanojoule = 10^{-9} joule

Table 20
Peak Power

<u>Peak Power</u>	<u>Estimated Accuracy Needed by Industry</u>	<u>Present NIST Capability accuracy / wavelengths</u>		<u>Improvement Achievable Without New Program accuracy / wavelengths</u>	
10 nanowatts	2%	] 10%	1.06 micrometers	6%	1.06 micrometers
1 milliwatt	0.25%				
1 kilowatt	0.25%				
100 kilowatts	1%	10%	1.06 micrometers	5%	10.6 micrometers
100 megawatts	2%				

Beam Quality Measurements

NIST's present program provides limited measurement support for only three of the twenty-two measured quantities listed as important to beam quality in Table 15.

pulse shape	small effort sufficient to support measurement of peak power at 1.06 micrometers with 10 nanosecond risetime
spectral purity	pilot effort leading to future work supporting near infrared laser diodes for optical fiber communications
noise	important effort being carried out for near infrared laser diodes for optical fiber communications as part of another new program, now partially funded, described in Chapter 5

Project 2. Laser Optics Performance and Quality Measurements

NIST present program provides no measurement support for the eleven quantities important listed as important to laser optics performance and quality in Table 16.

ENDNOTES

1. George A. Shukov and Al Smith, "Micromachining With Excimer Lasers", Lasers & Optronics, p. 76 (September, 1988).
2. This is the most common configuration for a laser. More complex configurations are also used.
3. The yttrium aluminum garnet (or "YAG") material is the host material for an embedded atomic element, usually neodymium, which is the actual source of the laser light (the "active" element). The structure of the embedded active element places this laser in the "atomic" class. The industry shorthand for the name of this laser is "yttrium aluminum garnet", so that shorthand will be used in this document.
4. Excimer lasers form molecules that are stable only when the participating atoms are in an electronically excited state. Common molecular lasers use molecules that are stable even when not in an excited state. Chemical molecular lasers combine atoms via a chemical reaction to produce molecules that are stable and in an excited state.
5. From a new study by Prognos AG of Basel, Switzerland, as cited in "\$103 Billion Seen for EO Market", Photonics Spectra, pp. 48-49 (December, 1988).
6. This conclusion is reached by totalling the estimated sizes of the markets for lasers (about \$2 billion) and the markets for the three laser-based products for which market data could be obtained: optical memories (\$6.6 billion from Japan alone), laser printers (\$3 billion), and barcode scanners (\$2.5 billion). Current market data for laser-based products in other applications have not yet been found, including data for big markets segments such as manufacturing, research and development, and medicine. Note that the present market size of at least \$14 billion per year exceeds the projections made several years ago: (1) Sales of \$10 billion were projected for 1990 for the "laser market" market, divided into \$6 billion (or 60%) commercial and \$4 billion (or 40%) military and government research and development. No distinction was made as to whether these figures referred to the U.S. versus the world market or to current versus constant dollars. "Current dollars" seems a safe assumption given the context in article: "The Laser Industry: Into the 1990s", Laser Focus, p. 8 (May, 1983). (2) A market of \$5 billion was projected for 1990 for the U.S. for lasers, laser services, and support equipment in 1982 constant dollars by Arthur D. Little, as reported in "Billions for Lasers", Photonics Spectra, p. 26 (April, 1984).
7. (1) A figure of \$720 million per year for 1989 for both captive and merchant transactions is provided by David Kales in "1989 Laser Economic Review and Outlook", Laser Focus World, p. 95 (January, 1989). Kales figures will be reflected in this document. (2) A somewhat smaller figure of \$660 million per year for 1989 is provided by Robert Clark, Richard Cunningham, Jeff Hecht, and Ron Iscoff in "The Laser Marketplace 1989", Lasers & Optronics, p. 38 (January, 1989). (3) Frost & Sullivan's data seem consistent with that of Kales in the following sense. In its 1987 report "Commercial/Industrial Lasers", Frost & Sullivan projects the U.S. market for commercial/industrial lasers (equivalent to Kales "commercial" lasers) at \$228 million for 1986 and \$315 million for 1991 with a real annual growth rate of 6.7% in between, yielding a level of about \$277 million for 1989. If this figure is compared with the decreasing U.S. market share noted by DeBenedictis of 38% in 1987, then the world market for 1989 should exceed $\$277 \text{ million} / 0.38 = \729 million [Len DeBenedictis, "Foreign Competition Poses Threat", Laser Focus World, p. 19 (January, 1989)]. (4) A somewhat larger figure is also suggested by two reports on data of Japan's Optoelectronics Industry and Technology Development Association (OITDA). First, Nagasawa and Forrest indicate that OITDA data for the year ending March 31, 1988 (i.e., primarily 1987) show that Japan alone produced \$305 million (41.2 billion yen) of laser semiconductor diodes compared to the \$180 million shown for 1988 worldwide production shown in Kales data. [Joe Nagasawa and Gary T. Forrest, "Japan Stakes Out Optical Semiconductor Market", Laser Focus World, p. 123 (January, 1989).] Second, a nearly identical OITDA figure for Japan's 1987 production of semiconductor laser diodes (42.2 billion yen) is cited in "Japan's Optoelectronics Industry Grew 18% in 1987", Laser Focus, p. 50 (July, 1988). The reason for the difference, which is about a factor of 2, is not known, but may be due to many factors, such as the possible inclusion in Japan's data of the cost of packaging the diodes for their intended applications, or the difficulty of capturing all of the value of lasers in captive markets as opposed to merchant markets.

8. The estimate of \$1.9 billion is a "best try" in the absence of proper data. The estimate is based on the following five steps of reasoning which contain a number of assumptions whose present accuracy is not known: (1) The world commercial market for lasers, inclusive of lasers used in government R&D, is \$720 million per year for 1989. [David Kales, "1989 Laser Economic Review and Outlook", Laser Focus World, p. 95 (January, 1989).] (2) The world market for all R&D lasers is \$159 million. [David Kales, "1989 Laser Economic Review and Outlook", Laser Focus World, p. 103 (January, 1989).] (3) The government component of the world market for lasers, laser equipment, and laser support services for 1985 was estimated at two-thirds of the world total; the remaining one-third was commercial. A similar distribution was estimated for 1983 for laser equipment and services. Laser services include contracted research and development of lasers. [Specifically, the 1985 U.S. market was projected at about \$2 billion, with government procurement accounting for two-thirds of the total, in the Arthur D. Little study cited in "Billions for Lasers", Photonics Spectra, p. 26 (April, 1984). Also, sales of laser equipment and services in the free world were cited as \$1.636 billion for 1983, with 34% commercial, 53% military, and 13% other government in "Laser Economic Review and Outlook: 17% Growth in 1983", Laser Focus, p. 10 (February, 1983).] (4) If we assume that the present "laser content" used for R&D scales with these fractions, then the world commercial market, corrected by removal of the lasers used for government R&D ($2/3 \times \$159 \text{ million} = \106 million), is \$614 million. (5) Finally, if we assume that the present laser content of the other categories of application also scales with the same fractions, then the total world market for the lasers themselves should be three times the corrected figure for the commercial market, or \$1.9 billion per year. However, this figure may be an overestimate because it is based on commercial/government fractions for 1985 when the military contribution to the government fraction was likely higher than it is today. This possible bias may account for the fact that relatively small amounts of laser sales are cited for world military purchases of some key laser types. For example, world military laser sales for three types of lasers (solid state yttrium aluminum garnet lasers, helium neon, and carbon dioxide lasers) are projected at only \$99 million for 1989 in the article by Kales in the citation that follows. Other laser types, such as chemical, free electron, and excimer lasers, are not included. [David Kales, "Slowdown Projected for Military Laser Market", Laser Focus World, p. 63 (January, 1989).]

9. David Kales, "1989 Laser Economic Review and Outlook", Laser Focus World, p. 95 (January, 1989). A lower estimate of 6.4% for 1988 to 1989 is provided by Robert Clark, Richard Cunningham, Jeff Hecht, and Ron Iscoff in "The Laser Marketplace 1989", Lasers & Optronics, p. 38 (January, 1989). The reason for such a great difference is not clear.

10. David Kales, "1989 Laser Economic Review and Outlook", Laser Focus World, p. 99 (January, 1989).

11. David Kales, "Buy American" Was the Cry Heard Around the Optics Industry in 1987", Laser Focus, p. 98 (November, 1987). The author does not indicate if the percentages reflect dollar fractions or parts-count fractions.

12. David Kales, "It's Export Time for U.S. Optics Makers", Laser Focus, p. 104 (November, 1988).

13. "Competitiveness in the U.S. Optics Industry: What's Missing", Laser Focus World, p. 59 (January 1989).

14. Of the 1988 U.S. shipments of laser optics to the world market, an estimated 23% were used internal to lasers and 77% were used external to lasers, according to data provided by Larry M. Giammona, "The 1988 Marketplace of Intracavity Laser Optics", Laser Focus, p. 114 (January, 1988). The U.S. figures are used above as estimates of the likely split of world laser optic shipments between internal and external laser optics.

15. From a new study by Prognos AG of Basel, Switzerland, as cited in "\$103 Billion Seen for EO Market", Photonics Spectra, pp. 48-49 (December, 1988).

16. Frost & Sullivan, Inc. in an announcement of "Commercial/Industrial Lasers", published in Summer 1987, indicates that the commercial market projected, in 1987, for 1989 is \$277 million or 38% of the figure provided by Kales for the same year. Comparison of figures from different studies always introduces an additional possibility of errors.

17. Len DeBenedictis, "Foreign Competition Poses Threat", Laser Focus World, p. 19 (January, 1989).
18. Len DeBenedictis, "Foreign Competition Poses Threat", Laser Focus World, p. 19 (January, 1989).
19. David Kales, "1989 Laser Economic Review and Outlook", Laser Focus World, p. 112 (January, 1989).
20. JTECH Panel Report on Opto- & Microelectronics, Science Applications International Corporation, p. 6-10 (May, 1985). The Japanese Technology Evaluation Program (JTECH) was initiated in 1983 by the U.S. Department of Commerce.
21. David Kales, "1989 Laser Economic Review and Outlook", Laser Focus World, p. 112 (January, 1989).
22. According to a report issued by Market Intelligence Research Company (Mountain View, California) as cited by Susan Walsh, "Industrial Lasers Continue Steady Climb", Managing Automation, pp. 18-19 (July, 1989).
23. Len DeBenedictis, "Foreign Competition Poses Threat", Laser Focus World, p. 19 (January, 1989).
24. "Competitiveness in the U.S. Optics Industry: What's Missing", Laser Focus World, p. 59 (January, 1989).
25. David Kales, "What's Ahead in Military Electro-Optics", Laser Focus, p. 91 (August, 1988).
26. David Kales, "Buy American" Was the Cry Heard Around the Optics Industry in 1987', Laser Focus, p. 98 (November, 1987). Optical components, as defined here, include those "used in laser-related applications (laser optics), other electro-optical systems, microscopes, telescopes, periscopes, and binoculars."
27. David Kales, "1989 Laser Economic Review and Outlook", Laser Focus World, pp. 102-103 (January, 1989). Note that Japan's Optoelectronics Industry and Technology Development Association suggests a higher figure for semiconductor lasers by claiming that Japan alone produced \$300 million of them in 1988, as noted by Paul Mortensen in "Japan's Optoelectronics Industry Grows 20%", Lightwave, p. 17 (April, 1989).
28. David Kales, "1989 Laser Economic Review and Outlook", Laser Focus World, pp. 98-99 (January, 1989). Figures from Clark show a similar pattern: semiconductor diodes (24,231,000), helium-neon (437,700), and all others (28,080). [Robert Clark, Richard Cunningham, Jeff Hecht, and Ron Iscoff in "The Laser Marketplace 1989", Lasers & Optronics, pp. 40-41 (January, 1989).]
29. David Kales, "1989 Laser Economic Review and Outlook", Laser Focus World, pp. 98-99 (January, 1989).
30. David Lytle, "U.S. Photonics Industry: Facing Premature Death?", Photonics Spectra, p. 36 (February, 1989).
31. Gary T. Forrest, "Market Performance Indicates Bright Outlook for Lasers in Japan", Laser Focus World, p. 112 (June, 1989).
32. Lewis M. Holmes, "Commercial Lasers 1988-89", Laser Focus World, pp. 67-68 (January, 1989).
33. Dennis Worth, "Small Lasers With a Big Future", Photonics Spectra, p. 143 (April, 1988).
34. Much of the material in this section comes from information provided by David Kales, "1989 Laser Economic Review and Outlook", Laser Focus World, pp. 95-114 (January, 1989). Additional examples of applications come from Lewis M. Holmes, "Commercial Lasers 1988-89", Laser Focus World, pp. 67-93 (January, 1989), and from "1989 Trends: Lasers", Photonics Spectra, pp. 111-120 (January, 1989). Many other articles are cited, as appropriate, in other notes.

35. David Kales, "1989 Laser Economic Review and Outlook", Laser Focus World, p. 99 (January, 1989).
36. This figure includes both therapeutic medicine (\$95 million) and diagnostic medicine (\$18 million).
37. Round-off error.
38. David Kales, "1989 Laser Economic Review and Outlook", Laser Focus World, pp. 98-99 (January, 1989).
39. Excimer lasers, which can produce very short wavelengths (ultraviolet range) may prove especially important for semiconductor lithography when linewidth requirements drop below 0.5 micrometers which is the linewidth required for 16 megabit dynamic random access memories (DRAMs). Gary T. Forrest, "Excimer Lasers Access Submicrometer Semiconductor Lithography", Laser Focus World, p. 23 (May, 1989).
40. Yvonne A. Carts, "Lucrative Niches Await Lasers in Semiconductor Processing", Laser Focus World, p. 105 (May, 1989).
41. "Laser-Welding Robots Tackle Automobile Production", Photonics Spectra, p. 139 (November, 1988). Susan Walsh, "Industrial Lasers Continue Steady Climb", Managing Automation, p. 18 (July, 1989).
42. Thomas A. Znotins, Darcy Poulin, and John Reid, "Excimer Lasers: An Emerging Technology in Materials Processing", Laser Focus, p. 54 (May, 1987).
43. Gary T. Forrest, "Market Performance Indicates Bright Outlook for Lasers in Japan", Laser Focus World, p. 112 (June, 1989).
44. The European Economic Community has launched the Eureka Project, which contains a Eurolaser Program, funded at \$74 million, to develop three types of industrial lasers (carbon dioxide, yttrium aluminum garnet, and excimer). [Uwe Brinkmann, "The EEC develops industrial lasers", Laser Focus World, p. 75 (May, 1989).] The U.K. Atomic Energy Authority's Culham Laboratory is leading a \$22.5 million program for building excimer lasers for cold machining of the hardest materials. [Brian Dance, "Culham will lead an excimer project", Laser Focus World, p. 76 (May, 1989).]
45. Roger Main, "Laser Robots Lend VW a Helping Hand", Lasers & Optronics, p. 42 (post August, 1987).
46. David Kales, "1989 Laser Economic Review and Outlook", Laser Focus World, p. 108 (January, 1989).
47. Bernhard H. Klimt, "Review of Laser Marking and Engraving", Lasers & Optronics, p. 61 (September, 1988).
48. Bernhard H. Klimt, "Review of Laser Marking and Engraving", Lasers & Optronics, p. 62 (September, 1988).
49. "Laser Lights Way to 3-D Prototypes", Photonics Spectra, p. 114 (January, 1989).
50. "Europe/U.S.: Three Vision Shows Spawn New Products", Lasers & Optronics, p. 30 (September, 1988).
51. George A. Shukov and Al Smith, "Micromachining With Excimer Lasers", Lasers & Optronics, p. 75 (September, 1988).
52. David Kales, "1989 Laser Economic Review and Outlook", Laser Focus World, p. 112 (January, 1989).
53. Some of the material in this section comes from Michael Moretti, "Medical-Laser Technology Responds to User Needs", Laser Focus World, pp. 89-102 (March, 1989). Other articles are cited, as appropriate.
54. C. Breck Hitz in a laser course presented at NIST in June, 1988.

55. Dennis L. Werth, "Laser Diodes Growing Up", Photonics Spectra, p. 133 (April, 1989). Frost & Sullivan, Inc. in an announcement of its market study "Medical Lasers", p. 1 (Spring, 1987).
56. Radical keratotomy corrects nearsightedness by changing the curvature of the cornea through small radial cuts made outside the visually significant central region. Corneal sculpting corrects nearsightedness and farsightedness by ablating a thin layer of corneal material from the visually important region. Thomas F. Deutsch, "Medical Applications of Lasers", Physics Today, p. 59 (October, 1988).
57. David Kales, "1989 Laser Economic Review and Outlook", Laser Focus World, p. 104 (January, 1989). The author does not indicate if the \$6 billion figure refers to laser sales, laser-based surgical equipment sales, surgical services, or some combination of these. He also does not indicate if he is referring to the world market, but that can be safely assumed since his entire article addresses the world market.
58. Comment by Jamie Dreyfuss, product marketing manager, Mitsubishi Electronics, as noted in "U.S. Fiber Market for Diode Lasers Will Reach \$1 Billion in 1990s", Laser Focus World, p. 11 (February, 1989).
59. "Resonant Leaky-Wave Antiguides Make High-Power Diode Laser Array", Laser Focus World, p. 9 (May, 1989). Philip Speser, "Doing Business in Space", Laser Focus World, p. 19 (May, 1989).
60. "CLEO '88 Takes in New Topics", Laser Focus, p. 116 (April, 1988). CLEO is the Conference on Lasers and Electro-Optics sponsored by the Optical Society of America and by the Lasers and Electro-Optics Society (LEOS) of IEEE.
61. David Begley, "Lasers for Spaceborne Communications", Photonics Spectra, p. 73 (February, 1989). David Begley and Bhogi Boscha, "Laser Diodes Conquer The Challenge of Space Communications", Photonics Spectra, p. 147 (April, 1989).
62. David Kales, "1989 Laser Economic Review and Outlook", Laser Focus World, pp. 98-99 (January, 1989).
63. Paul Mortensen quoting figures of Japans' Optoelectronics Industry and Technology Development Association (OITDA) in his article "Japan's Optoelectronic Industry Grows 20%", Lightwave, p. 17 (April, 1988).
64. Business Communications Co. in an announcement of its study "Optical Disks: Markets, Technology, Materials" (March, 1989). The announcement did not specify if the market value cited referred to unrecorded or recorded discs.
65. Arnold Mayer and Norbert Schroder, "Opto-Electronic Components and Systems" by Prognos AG of Basel, Switzerland (August, 1988).
66. Data provided by the Electronic Industries Association for total compact disc players which includes "Home CD PLayer, Audio Systems sold with CD Players, Portable CD Players (Including Combinations), and Autosound CD Players". The dollar figure of \$1 billion is based on an estimate of a \$200 factory-to-dealer price for each unit's CD-player content.
67. Business Communications Co. in an announcement of its study "Optical Disks: Markets, Technology, Materials" (March, 1989).
68. From synopsis of the study "Office Productivity Impact Using Optical Image Storage and Retrieval" by Electronic Trend Publications (September, 1988). The increase reflects an average compound rate of growth of 81 percent per year for the four-year period. Dataquest projects a similar rate of growth over most of the same period but starts from a smaller estimate of the 1988 level of \$511 million, in "Research Newsletter: Dataquest's Electronics Industry Forecast", p. 6 (May, 1989).

69. After correction of some outyear calculations, these percentages were produced from data by Dataquest, "Research Newsletter: Dataquest's Electronics Industry Forecast", p. 6 (May, 1989).
70. Linda W. Helgerson, "Bean-Counting Techniques for CD-ROM Drives: Installed Base & Annual Sales -or- Speed of User Acceptance Given an Appropriate Application", CD-ROM EndUser, p. 33 (March, 1989). Ms. Helgerson cites the world market for CD-ROMs at 70k-100k units in 1988, 100k-150k units in 1989, and 210k-250k units in 1990 (84% growth rate in 1990). At about \$1000 per unit, this amounts to \$0.2 billion to \$0.3 billion in 1990.
71. Leigh Rivenbark, "CD-ROM and Uncle Sam", Federal Computer Week, p. 40 (June 26, 1989). The dollar levels shown were computed by applying an average price of \$600 per drive for 1989, suggested by the article, to the volume of drives stated in the article. For 1993, values of \$600 and \$300 per drive were used to reflect the effects of a possible reduction in unit cost with increasing volume.
72. David Kales, "1989 Laser Economic Review and Outlook", Laser Focus World, p. 112 (January, 1989). The author does not explicitly indicate that the \$3 billion is a world market figure, but that can be safely assumed from the fact that his entire article is addressing the world market.
73. Arnold Mayer, Norbert Schroder, "Opto-Electronic Components and Systems" by Prognos AG of Basel, Switzerland (August, 1988).
74. Robert E. Hopkins, "Optical System Requirements for Laser Scanning Systems", Optics News, p. 11 (November, 1987). A "pixel" is a dot, the smallest element of picture information generated.
75. Laser radar is often called "lidar" for light detection and ranging. Laser radar is also sometimes called "ladar" for laser detection and ranging.
76. "\$2-Million Ozone Lidar System Ships to Japan", Laser Focus, p. 28 (June, 1988).
77. Yvonne A. Carts, "Laser Radar: Solid-State Lidar Development Promises Longer Lifetimes", Laser Focus World, p. 23 (June, 1989).
78. Yvonne A. Carts, "Laser Radar: Solid-State Lidar Development Promises Longer Lifetimes", Laser Focus World, p. 23 (June, 1989).
79. Emmett W. Chappelle, Darrel L. Williams, Ross F. Nelson, and James E. McMurtrey III, "Lasers May Help in Remote Assessment of Vegetation", Laser Focus World, p. 123 (June, 1989). The authors are from the National Aeronautics and Space Administration and the U.S. Department of Agriculture.
80. Emmett W. Chappelle, Darrel L. Williams, Ross F. Nelson, and James E. McMurtrey III, "Lasers May Help in Remote Assessment of Vegetation", Laser Focus World, p. 123 (June, 1989). The authors are from the National Aeronautics and Space Administration and the U.S. Department of Agriculture.
81. "Laser Detects Herbicide on Tobacco", Lasers & Optronics, p. 26 (September, 1988).
82. Bernhard H. Klimt, "Review of Laser Marking and Engraving", Lasers & Optronics, p. 61 (September, 1988). Klimt indicates that "marking and bar coding represent a \$2.5 billion-per-year industry" and that marking is only 1 to 2% of the combined market; thus virtually the entire \$2.5 billion is bar coding. Klimt does not indicate whether the market he is characterizing is U.S. or world, but world is probably intended and will be assumed here. Certainly that assumption will not overstate the world market.
83. Robert Clark, Richard Cunningham, Jeff Hecht, and Ron Iscoff in "The Laser Marketplace 1989", Lasers & Optronics, p. 46 (January, 1989).

84. The Department of Transportation (FAA) is requiring that wind shear detection systems be installed on 3600 jetliners within four years. While costs vary with the type of aircraft, an estimate of \$50,000 per aircraft has been mentioned leading to a total cost of \$0.2 billion. FAA is not specifying the technology to be used; the marketplace will decide. Microwave radar, laser radar, and passive infrared systems are the primary candidates for forward looking detection. FAA and NASA are jointly investing \$24.8 million over five years (beginning in 1987) to stimulate development of advanced wind shear detection systems in their Forward Looking Technology Program. The systems are described in Airborne Wind Shear Detection and Warning Systems: First Combined Manufacturers' and Technologists' Conference, Federal Aviation Administration, U.S. Department of Transportation, and National Aeronautics and Space Administration (January, 1988).
85. Yvonne A. Carts, "Laser Radar: Solid-State Lidar Development Promises Longer Lifetimes", Laser Focus World, p. 23 (June, 1989).
86. David Kales, "1989 Laser Economic Review and Outlook", Laser Focus World, p. 99 (January, 1989).
87. Frost & Sullivan, Inc., The Military Laser Market in the U.S., p. 1 (June, 1986). The data were also reported in "Military Laser Sales: The Forecast is Cloudy", Photonics Spectra, p. 79 (January, 1987).
88. Frost & Sullivan, Inc., The Military Laser Market in the U.S., p. 10 (June, 1986).
89. Report by the National Measurement Requirements Committee, National Conference of Standards Laboratories, NMRC 89-01, p. 1-1 and Chapter 4 (January, 1989). The survey was conducted in 1982 and was updated periodically through 1988.
90. The particular time interval of relevance for frequency stability, and for other measured quantities in this table, is dependent on the particular application being supported.
91. Important to data and communications applications.
92. Applies to low-power laser light only, where individual photons can be counted. Important for basic research in lasers and optics and for atmospheric propagation studies and interferometry.
93. Spectral purity of 1 part in 10^{10} is required for coherent optical fiber communications. Spectral purity of 1 part in 10^{13} is required for laser gyros.
94. The phase front measurement determines the degree to which an array of diode lasers looks like a single laser from a distance, that is, how well the lasers are working together.
95. Spectral purity measurements for the low frequency (near infrared) laser diodes designed for optical fiber communications will be developed with resources being pursued separately. Spectral purity measurements for other lasers, which operate at a much greater diversity of frequencies, will be addressed by the expanded program addressed here.
96. The work on refractive index will focus primarily on the development of reference data for important laser optic materials.
97. Key tasks include the determination of the variation with temperature of both electro-optic and magneto-optic properties. These properties enable electronic manipulation of laser beams, including shuttering and modulation.
98. Existing definitions for similar quantities, such as "modulation transfer function" or "optical transfer function", are valid only for ordinary (incoherent) light.

Chapter 8 MICROWAVES New Program Plan

Summary

Microwave systems are critical to the national economy, the national safety, and the national security. The U.S. relies on high performance microwave systems to provide corporate communications, to land airplanes safely, to warn of weather disasters, to conduct international affairs of state, and to defend the nation. In these capacities, microwave systems serve as the eyes of the nation and the backbone of its worldwide communications networks.

The amount of microwave equipment that these and other microwave services require is vast and growing. Present U.S. shipments of microwave equipment are estimated at \$35 billion per year and account for 1/7 of all electronic equipment, systems, and components shipped in the U.S., valued at \$248 billion for 1988. Worldwide shipments of microwave equipment are estimated at \$81 billion per year and are expected to reach \$143 billion per year in the year 2000 (1988 dollars).

The growth in the worldwide market for microwave systems arises from both traditional applications, like those mentioned above, and emerging applications. Emerging applications include: microwave electronics for high definition television (HDTV), for fiber optic communications, and for computer circuitry; vision systems for robots; on-board wind-shear detection systems for airplanes; collision-avoidance radar for automobiles; direct broadcast systems employing satellites; and local communications and radar systems for industrial and corporate applications.

The nations that will win the expanding worldwide market must successfully pursue three revolutionary changes in microwave electronics: extraordinary performance levels; integration; and higher frequencies.

Extraordinary performance levels mean improving speed, signal quality, sensitivity, versatility, and flexibility. These improvements are needed to increase information handling capacity and to open new applications areas.

Integration means integrating microwave electronic devices with each other, with optoelectronic devices, and with antennas. Integration is necessary to reduce the size, cost, and weight of microwave systems and to increase their power and versatility.

Exploitation of the higher frequencies means opening frequencies in the region from 30 GHz to 1000 GHz to greater use, or to first use, in order to gain access to the additional spectral space and special properties that they offer.

These changes in microwave technology are just as significant as those that occurred in semiconductor technology when integrated circuits replaced transistors and tubes. In fact, that is exactly what is in happening now for microwave technology. These are exciting changes. They will ultimately lead to powerful new products, such as entire microwave systems on

individual wafers a few inches in diameter. Each wafer will contain an electronically steerable antenna and integrated electronics for transmission, reception, and signal processing. Such "microwave systems on a chip" will support robot vision, automobile radar, and other applications.

However, the promises implicit in advanced microwave technology cannot be realized without dramatic improvements in measurement support. NIST has long been aware of the shortfall in its resources to meet industry's measurement needs. Industry executives, through the IEEE's Committee to Promote National Microwave Standards, and industry and Government representatives, through the National Conference of Standards Laboratories, have decried the lack of NIST measurement support for industry, have surveyed the needs, and have spelled out the action needed from NIST.

NIST's response is this new program. NIST proposes to build a new microwave measurement technology program in order to provide advanced measurement support for high performance microwave components in three classes: (1) individual components, including antennas, for 1-100 GHz; (2) integrated circuits and integrated antennas for 1-100 GHz; and (3) integrated circuits and integrated antennas for 100-1000 GHz.

This new measurement program will provide the measurement capability needed to accelerate R&D toward new products, to improve quality control during manufacturing, to provide the basis for voluntary industry standards for compatibility and other aims, to support the specification and procurement of microwave products, to improve access of U.S. products to international markets, and to assure U.S. international competitiveness in one of the largest segments of the world market for electronic products.

Organization of this Document

In this document, the following topics are discussed:

- (1) Definition of Microwaves
clarification of terminology
- (2) Capabilities and Limitations of Microwaves
technical description of the capabilities and limitations of microwaves,
needed for understanding the following material
- (3) Microwave Electronics Markets
the size and nature of microwave markets, and the expanded or new
services demanded by those markets
- (4) Technical Goals for Industry in Response to Marketplace Demands
the technical goals that industry must achieve if its products are to meet
the demands of the marketplace
- (5) NIST Measurement Support for Industry's Technical Goals

the measurement capability that NIST will develop to enable industry to achieve its technical goals

Definition of Microwaves

Microwaves are radiated electromagnetic energy just like the radio waves used for radio and television broadcasts, except that microwaves are about 1000 times higher in frequency. Lightwaves are similar to microwaves, but are even higher in frequency, about another 1000 times higher.

Table 1
Overview of Frequency Spectrum

Megahertz (MHz) = 10^6 Hz	medium frequency waves very high frequency waves ultra high frequency waves	AM radio FM radio, TV, etc. TV, other
Gigahertz (GHz) = 10^9 Hz	centimeter waves millimeter waves sub-millimeter waves	] MICROWAVES
Terahertz (THz) = 10^{12} Hz	far infrared light near infrared light visible light	
Petahertz (PHz) = 10^{15} Hz	ultraviolet light x-rays	

Microwaves have frequencies in the range of 1-1000 GHz.¹ Most microwave systems today operate in the range of 1-30 GHz; but frequencies up to 100 GHz are increasingly used, and applications to 300 GHz and even to 1000 GHz are in the offing. Microwaves get their name from the fact that they travel through the atmosphere as closely spaced waves. If microwaves could be made visible, they would look like a succession of small ripples, much like the ripples that move across a pond when a rock is dropped in it. The distance from one ripple to another in a microwave is called the wavelength and is usually measured in centimeters or millimeters, hence the terms "centimeter waves" and "millimeter waves" for key portions of the microwave spectrum.

Microwaves are an important part of the frequency spectrum available for our use. This frequency spectrum is limited in capacity because a given frequency cannot be used by two systems at the same time in the same location without mutual interference. The demand for

¹The term "microwaves" is sometimes used to represent frequencies in the range of 1-30 GHz. Here "microwaves" will be used to represent all frequencies in the range of 1-1000 GHz. The terms centimeter waves, millimeter waves, and sub-millimeter waves will be used to distinguish among the types of microwaves.

certain frequencies within the spectrum is high, so many conflicts arise. Often these conflicts are international in scope and must be resolved by international bodies.²

Communication systems that employ microwaves consist of many electronic components. At the transmission end of a microwave system, electronic devices create and amplify the microwave beam and place information on it. Antennas radiate the beam toward the receiving area. At the receiving end, other antennas capture the incoming beam and other electronic devices remove the information from it. All of these components must work well to preserve the fidelity of the information on the beam. The measurements developed for microwave systems must assure that all functions necessary to accomplish this goal work correctly.

Radar systems work much like communication systems except that they use the same antenna for transmission and reception and they send out a pulsed beam of microwaves, rather than a continuous beam.

Capabilities and Limitations of Microwaves

Microwaves have inherent capabilities and limitations relative to radio waves of lower frequency. The degree to which the capabilities can be realized in real microwave electronics depends on the development of sophisticated microwave technology that is highly measurement intensive.

High information capacity: Microwaves can carry very large amounts of information. This capacity results from the fact that microwaves have a very high frequency. All radio waves, including microwaves, can carry information in proportion to their frequency. For example, microwaves can carry 1000 times more information than radio waves used for AM and FM radio. Put another way, one microwave signal can carry all of the program material of 1000 AM radio stations simultaneously. This high information capacity is important both to telecommunications applications and to signal processing applications.

Line-of-sight transmission: When microwaves are radiated by antennas, they travel in a straight, line-of-sight manner. This is true because microwaves, unlike radio waves of lower frequency, pass right through the ionosphere, which is the electrically charged atmospheric layer surrounding the earth. For this reason, microwaves cannot work their way around the globe by bouncing back and forth between the earth and the ionosphere, as radio waves of lower frequency can do. Instead, microwaves must be relayed along the surface of the earth from one microwave tower to another, or they must be transmitted to satellites that retransmit them downward to desired locations or that relay them to other satellites for retransmission downward. This line-of-sight characteristic is a limitation for some applications. For other applications, it is an advantage: it helps prevent interference among different microwave systems operating on the same frequency.

²The World Administrative Radio Conference meets every four years under the aegis of the International Telecommunications Union to make the frequency allocations, and the International Frequency Registration Board keeps track of the allocations.

Highly focused: Microwaves can be focused into narrow beams much more easily than radio waves of lower frequency. In this sense microwaves approach the characteristics of light; light is readily focused by reflectors like those in flashlights. Because microwaves can be focused, their energy can be delivered to small nearby receiving antennas or to entire geographical areas, such as entire states, from remote satellites. Also, because of focusing, two or more microwave beams can be directed to adjacent areas without mutual interference, even if they operate on the same frequency. This characteristic improves efficiency in the use of the microwave portion of the frequency spectrum.

Small antennas: The high frequencies of microwaves reduce the size of the antennas needed to achieve a given degree of focusing. This fact reduces the cost of microwave systems and increases the diversity of applications that they can serve. For example, the relatively small size of microwave antennas makes them suitable for roof-top mounting for corporate communications systems. The size advantage also facilitates mobile applications in automobiles, airplanes, satellites, and space vehicles. The size reduction is particularly important for the design of highly focused antennas, since antennas with high focusing are larger than those with less focusing at a given frequency. Even very highly focused microwave antennas can be tolerable in size (several meters); antennas with comparable focusing at lower frequencies would be impossibly large.

Atmospheric interactions: The higher frequencies of the microwave family (the millimeter-wave and sub-millimeter-wave frequencies) interact more with the atmosphere than do radio waves of lower frequency. This interaction limits the distances over which these microwaves can travel through the atmosphere, a problem for some applications. For other applications, this interaction is an asset: it enables the use of microwaves to sense weather conditions that radio waves of lower frequency cannot "see"; and it enables limiting a transmission to a controlled distance to reduce unwanted reception by nearby users or unwanted interference with them when they are operating on the same frequency. This characteristic is particularly important when using millimeter waves for local applications such as local communications systems or local radar systems for monitoring moving objects. In free space, atmospheric interactions are not a problem, even for satellite-to-satellite communications, since satellites orbit well above the atmosphere.

Metal/earth interactions: Microwaves interact more sensitively with conducting objects, including the earth, than do radio waves of lower frequency. Therefore, they are effective for radar, navigation, guidance, and remote sensing (geological, agricultural, and weather sensing).

High spatial resolution: The higher frequencies in the microwave spectrum provide high spatial resolution. High resolution is particularly important for radar systems since it allows them to "see" objects more clearly and thus to identify them more accurately.

Optoelectronic technology: Microwave technology can be integrated with optoelectronic technology to provide powerful capabilities that are not achievable by either technology alone. For example, microwave technology is now being used to place information on lightwaves in experimental optical fiber systems. This new approach has produced the highest information

rates yet achieved in optical fiber systems.³ Conversely, optical fibers show promise for use in large microwave antennas; and embedded optical waveguides show promise for use in integrated microwave antennas and in microwave satellite systems.⁴

Note in the above discussion that microwaves are repeatedly associated with smallness: small waves, measured in centimeters and millimeters; small antennas; and fine scales of resolution for radar. All of these characteristics derive from the high frequencies of microwaves. However, as noted earlier, the special properties of microwaves can only be fully exploited with sophisticated microwave technology, and that technology is very measurement intensive.

Microwave Electronics Markets

U.S. Outlook

U.S. shipments of microwave equipment are estimated at \$35 billion for 1988.⁵ Microwave equipment represents 1/7 of all U.S. shipments of electronic equipment, systems, and components, valued at \$248 billion in 1988.⁶ Only one other equipment category has greater shipments: computers and their peripherals.

Most microwave equipment falls in the category "radio communications and detection equipment" (SIC Code 3662)⁷. For this reason, the performance of this category provides the best documented estimator we have of the outlook for U.S. shipments of microwave equipment. U.S. shipments of all equipment in this category were valued at \$54 billion in 1988 and are expected to grow at 4% in 1989 and at 5% per year for the following five years in real terms (exclusive of inflation), according to the Department of Commerce.⁸ If these rates of growth are applied to the microwave content of U.S. shipments (\$35 billion in 1988) through 1994, and if the 5% rate continues to the year 2000, then the levels of microwave shipments, in constant 1988 dollars, shown in Table 2 will result.

³"Lasers", Fiber Optic News, page 4 (April 4, 1988). The potential for microwave electronics in fiber optic systems is further discussed by Jeff Montgomery and John Ryan, "Leap Seen for Microwave Fiber-Optics", Microwaves & RF, Vol. 26, No. 6, p. 53 (June, 1987), and by Robert Olshansky, "Promising Merger of Microwave and Lightwave", Lightwave, p. 25 (January, 1988).

⁴M. Lawrence, "Optics Illuminate Next-Generation Radar Systems", Microwaves & RF, p. 165 (June, 1988). Jeff Montgomery and John Ryan, "Leap Seen for Microwave Fiber-Optics", Microwaves & RF, p. 53 (June, 1987).

⁵Microwave equipment shipments are not tracked as an independent data category in the current Standard Industrial Classification (SIC) System of the U.S., so the exact levels are difficult to determine. The figure shown here is based on an estimate that U.S. shipments represent about 95% of those for North America as a whole. The North American production is estimated as \$36.8 billion for 1988 by Jeff D. Montgomery of ElectroniCast Corporation in "Microwaves to 2013", Microwave Journal, Vol. 31, No. 9, pp. 259-272 (September, 1988).

⁶1989 Electronic Market Data Book, Marketing Services Department, Electronic Industries Association, pp. iii, 3 (1989).

⁷SIC means Standard Industry Classification System.

⁸1989 U.S. Industrial Outlook, International Trade Administration, U.S. Department of Commerce, pp. 27-1 to 27-3 (1989).

Table 2
Projected Growth of U.S. Microwave Equipment Shipments

	Billions of Dollars		
	<u>1988</u>	<u>1994</u>	<u>2000</u>
Constant 1988 dollars (no inflation)	35	46	62

The enormous size of U.S. shipments of microwave equipment reflects the broad range of services that microwave systems already provide: communications; navigation; radar; guidance; remote sensing (geological, agricultural, and weather); electronic warfare; test and measurement; industrial applications; consumer applications; and others. The demand for new or emerging services will keep the shipments of microwave equipment high. Examples of new or emerging services include: on-board wind shear detection systems for airplanes; improved radar systems for weather forecasting; collision avoidance radar systems for automobiles⁹; low-power high-speed communications systems for local environments¹⁰; local radar systems for monitoring and controlling moving objects¹¹; vision and control systems for robotics; high speed computer circuits; signal processing for high speed fiber optic communications systems; signal processing for high definition television (HDTV); and local bypass facilities for corporate communications.¹² Other new or emerging applications require satellites. Examples include: television receive-only systems associated with direct broadcast satellite (DBS) service¹³; satellite mobile systems; direct business use of satellites for video programming; and end-to-end facility bypass networks. The last two are already major industries. Many of the others have the potential to become so.

⁹West Germany is in the lead. AEG Ag has announced imminent introduction of an integrated circuit chip containing a millimeter-wave receiver, with a projected cost as low as \$15, suitable for communications systems and automobile radar.

¹⁰Japan's Key Technologies Research & Development Center is investing 45 million yen to develop this flexible new communications product for frequencies from 10 kHz to 1000 GHz.

¹¹Japan's Key Technologies Research & Development Center is investing 120 million yen to develop remote monitoring and control systems using millimeter waves, capable of handling 100 units of moving objects in natural environments within a 2 kilometer radius to assure safe functioning.

¹²"Facility bypass networks" bypass local public telephone networks to achieve one or more of these aims: "reduce costs, improve service quality, and offer greater security, reliability, and service flexibility". They are usually implemented with microwave systems since the installation of custom cable systems is too expensive and far less flexible. The Department of Commerce indicates, in a review of studies of the subject, that "16-29 percent of large-volume telephone company customers are bypassing their local telephone companies". "End-to-end facility bypass networks" bypass both local and long distance lines of public telephone networks. 1988 U.S. Industrial Outlook, U.S. Department of Commerce, International Trade Administration, p. 33-3.

¹³Japan is in the lead.

U.S. Government Purchases

Of the \$54 billion of equipment in the category "radio communication and detection equipment" (SIC Code 3662), \$26 billion or 48% was purchased by the U.S. Government. Of that \$26 billion, \$23 billion or 43% of the \$54 billion, was purchased by the Department of Defense, according to the Department of Commerce.¹⁴ These figures provide the best documented estimators we have of the fraction of microwave equipment purchased by the Government.

While the DOD is expected to remain the largest Government purchaser of microwave equipment, other Government agencies are increasingly involved in making, stimulating, or approving major uses of microwave equipment. The Departments of Transportation, Commerce, and State, and the Federal Communications Commission and the National Aeronautics and Space Administration provide examples:

The Department of Transportation (FAA) is currently participating in a \$5-6 billion procurement of microwave equipment to upgrade the microwave systems at 100 U.S. airports. The new systems include: (1) communications systems for exchange of information between airplanes and control towers; (2) landing systems for aircraft; (3) radar systems for monitoring weather; and (4) radar systems for monitoring the movement of airplanes in the air and on the ground.¹⁵

The Department of Commerce is the principal partner in a related three-agency \$0.5 billion procurement for NEXRAD, the next generation of weather radar. By the mid 1990s, 175 NEXRAD systems are slated for installation.¹⁶

The Department of Transportation (FAA) is requiring that wind shear detection systems be installed on 3600 jetliners within four years. While costs vary with the type of aircraft, an estimate of \$50,000 per aircraft has been mentioned leading to a total cost of \$0.2 billion.¹⁷ FAA is not specifying the technology to be used; the marketplace will

¹⁴1989 U.S. Industrial Outlook, International Trade Administration, U.S. Department of Commerce, p. 27-1 (1989).

¹⁵Information provided by the FAA. The system is described in the National Airspace System Plan, Federal Aviation Administration, U.S. Department of Commerce (June, 1988). A discussion of the new system appears in "Why Tomorrow's Skies will be a Whole Lot Safer", Business Week, pp. 99, 102 (September 5, 1988). The new "Microwave Landing System" (MLS) will replace the present "Instrument Landing System" (ILS) used since the mid-1940s. The first MLS has been installed as a demonstration unit. Compared to ILS, MLS will support landings from multiple directions at different speeds and angles of descent, at a faster rate, and with less susceptibility to surrounding terrain, weather, and radio interference. The International Civil Aviation Organization wants microwave systems installed at 200 airports by 1998. "Microwave Landing System Installed", Electronic Engineering Times, p. 48 (April 17, 1989).

¹⁶Performance, Unisys Defense Systems Issue, p. 5 (Spring/Summer, 1988).

¹⁷"Wind-Shear Devices to Be Required on Jets", Washington Post, p. A19 (September 27, 1988).

decide. Microwave radar, laser radar, and passive infrared systems are the primary candidates for forward looking detection.¹⁸

The Department of State has issued a request for proposals for a new worldwide telecommunications network that will cost up to \$0.7 billion. It will contain a mix of microwave and fiber optic communications technologies and computers.¹⁹

The Federal Communications Commission has just approved the launching of 23 new communications satellites, valued at \$4 billion.²⁰

The National Aeronautics and Space Administration, in cooperation with the National Oceanic and Atmospheric Administration of the Department of Commerce, is actively evaluating the merit and design of an Earth Observing System, composed of four to six satellites to monitor long-term changes in the earth's atmosphere, magnetic field, geology, etc. The project is collaborative with Japan and the European Community. U.S. costs for the system would be \$2 billion to \$4 billion over ten years. The system would rely critically on advanced microwave and optical equipment.

World Outlook

The world market for microwave equipment is estimated to be 2.1 to 2.5 times the size of the U.S. market alone.²¹ If one assumes the median value of 2.3 and a real growth rate of 4% for 1989 and 5% for the following five years, identical to the pattern projected by DOC for the next six years for the U.S. alone, and if the 5% rate is further assumed to apply to the year 2000, then the levels of microwave shipments, in constant 1988 dollars, shown in Table 3 will result.

¹⁸FAA and NASA are jointly investing \$24.8 million over five years (beginning in 1987) to stimulate development of advanced wind shear detection systems in their Forward Looking Technology Program. The systems are described in Airborne Wind Shear Detection and Warning Systems: First Combined Manufacturers' and Technologists' Conference by the Federal Aviation Administration, U.S. Department of Transportation, and National Aeronautics and Space Administration (January, 1988).

¹⁹The project is described in Department of State Telecommunications Network, Request for Proposal, U.S. Department of State (October, 1988).

²⁰"FCC Okays \$4B in Satellite Launchings", Electronic Engineering Times, p. 38 (January 16, 1989).

²¹Again, good figures are lacking, but estimates can be made based on estimates of world market sizes for categories containing a lot of microwave equipment. Dick Anderson, Vice President and General Manager of the Microwave and Communications Group of Hewlett-Packard, has provided one of those estimates in a talk at Test and Measurement Trends and Technologies - Editorial Seminar, sponsored by Hewlett-Packard (April 6, 1988).

Table 3
Projected Growth of World Microwave Equipment Shipments

	Billions of Dollars		
	<u>1988</u>	<u>1994</u>	<u>2000</u>
Constant 1988 dollars (no inflation)	81	106	143

The large size of the world market for all microwave equipment is reflected in the large size of the world market for the microwave test equipment required to support microwave systems. In 1988 the world market for microwave test equipment alone was \$1.2 billion. That market is growing at a nominal rate (inclusive of inflation) of 14.1% per year and thus is expected to reach \$2.2 billion by 1993.²²

The U.S. is not penetrating the non-U.S. portion of the world market for all microwave equipment well. For example, U.S. exports in the category of "radio communication and detection equipment" (SIC Code 3662) were only \$4.5 billion in 1988. Imports were higher at \$5.0 billion, yielding a negative balance of trade and an export/import ratio of 0.9. Japan supplies 48% of all U.S. imports in this category, four times the contribution of any other country. Only 9% of U.S. exports of microwave equipment go to Japan.²³ In summary, the U.S. has a lot to gain by better penetration of the world market, and a lot to lose by increased penetration of its own market.

Current data on the performance of other countries in the world market for microwave equipment are difficult to obtain, but data for 1981 for telecommunications equipment indicate the strength of the chief competitors of the U.S.: Japan, Canada, and Europe. In that year, the U.S. still had a favorable balance of trade with an export/import ratio of 1.3. The competing nations did even better. As shown in Table 4, they exported more than the U.S. in 1981 and achieved a higher ratio of their own exports to their own imports. Since 1981, the U.S. export/import ratio has declined to 0.9, as noted above.

Competing factors will affect the growth of the world market for microwave equipment. On the one hand, the demand for the services of microwave systems is rising, especially as new applications are identified. On the other hand, the cost of microwave equipment will fall if microwave integrated circuits and integrated antennas can be successfully developed. These cost reductions will be significant (factors of 100). As a result, the first nations to successfully commercialize microwave integrated circuits and antennas will gain a tremendous advantage in both the U.S. market and the international market for microwave products. The cost reductions, in turn, will inevitably open larger markets for microwave products.

²²Lloyd D. Resnick and Martin R. Stiglitz discuss the findings of Market Intelligence Research Company's report "World Microwave Test Equipment Markets II" in their article "The World Microwave Test Equipment Market", Microwave Journal, pp. 40-47 (December, 1988).

²³1989 U.S. Industrial Outlook, International Trade Administration, U.S. Department of Commerce, p. 27-2 (1989).

Table 4
1981 Telecommunications Equipment Trade Data²⁴

	<u>Exports/U.S. Exports Ratio</u>	<u>Export/Import Ratio</u>
U.S.	1.0	1.3
Japan	1.4	19.8
Canada	2.2	2.1
Europe	4.6	3.8

The Japanese are among the nations that are pushing hard to develop microwave integrated circuits, driven almost exclusively by consumer applications. They are highly interested in direct broadcast satellites, in mobile radio transmission systems, and in microwave electronics for optical fiber transmission systems with high data rates and for signal processing for high-definition television (HDTV).²⁵ The Japanese have proven their ability to be competitive in telecommunications components. According to a recent NSF/DARPA assessment of Japan's telecommunications technology, "The components it [Japan] introduces into the market are increasingly the most advanced in technical characteristics and quality and the lowest in cost. Japan is verging on international market dominance at the components level."²⁶

The Europeans are driving hard, too, with a special emphasis on telecommunications applications of microwave technology. They have become major standard setters in this field.

Impact of Optical Fibers

The emergence of optical fiber systems will affect the demand for microwave equipment but in a limited manner only, for two reasons. First, the demand for communications services is so high that all available means of transmitting data will be needed. Second, the emergence of optical fibers affects primarily one type of microwave service: point-to-point communications between areas of high population density. For other types of services, microwave technology will continue to dominate and expand: point-to-point communications services for areas of low population density; point-to-multipoint communication services in all areas; mobile communication services for land, sea, air, and space; sensing, including geological, agricultural, and weather sensing; radar; navigation; guidance; electronic warfare; industrial applications; and consumer applications. These microwave services require one or more of the characteristics that cable technology cannot provide, as shown in Table 5.

²⁴The Telecommunications Industry, International Trade Administration, U.S. Department of Commerce, p. 21 (April, 1983). Focuses on SIC Code 3661 only.

²⁵Far East Scientific Bulletin 11 (1), U.S. Office of Naval Research, p. 112 (January-March, 1986).

²⁶JTECH Panel Report on Telecommunications Technology in Japan - Final Report, Science Applications International Corporation, p. xi (May, 1986). The Japanese Technology Evaluation Program (JTECH) "was initiated in 1983 by the U.S. Department of Commerce; currently the National Science Foundation is the lead supporting agency."

Table 5
Microwave Capabilities That Cable Cannot Provide

<u>Capability</u>	<u>Applications Exploiting the Capability</u>
area coverage	communications, sensing, radar, navigation, guidance, electronic warfare, consumer applications
movement	communications with satellites or mobile vehicles including automobiles, aircraft, ships, and spacecraft; radar
flexibility	communications, electronic warfare
microwave energy	industrial, medical, and consumer applications

"Flexibility" requires clarification. It takes several forms: (1) Microwave systems can be set up quickly without the need to resolve the difficult right-of-way problems that arise when laying cable. (2) Microwave installations are less sensitive to variations in the terrain than cable installations. (3) Satellite and terrestrial microwave systems can be reconfigured readily to serve different geographical areas and new users. (4) Satellite systems can serve vast areas of low population density just as easily as small areas of high population density. Because of this flexibility, microwave systems can serve in both permanent installations and temporary installations such as those used for emergencies.

While optical fiber technology does compete with microwave technology for some communications applications, the more salient relationship between the technologies is complementary or even symbiotic.²⁷ For example, microwave systems will provide "local area" delivery for signals carried across the country by optical fibers, particularly when mobile subscribers are involved. In fact, microwave and optoelectronic technologies will gradually merge as optoelectronic technology takes on functions in microwave systems and microwave technology takes on functions in optical fiber systems. Together, they will provide levels of performance that neither can achieve alone.

Technical Goals for Industry in Response to Marketplace Demands

To meet the demand for expanded and new microwave services and to compete internationally, U.S. industry must pursue three technical goals for microwave systems:

- Goal #1: Improved performance
- Goal #2: Reduced cost, size, and weight
- Goal #3: Improved access to higher frequencies

²⁷"The Evolving Symbiosis of Optical Fiber, Satellites", Washington Post, pp. H-1 and H-5 (August 21, 1988). Also, George Heiter of AT&T Bell Laboratories, "Personal View: Systems Integration", Microwaves & RF, p. 126 (May, 1988).

To achieve Goal #1 of improved performance, industry must pursue higher information density, improved signal quality, and expanded versatility and flexibility:

Higher information density can be achieved by increasing the information capacity of existing systems and by enabling a greater number of systems to operate without mutual interference in a given region. These advances are highly important because crowding is becoming increasingly serious as additional terrestrial systems come into use. In space, crowding will become of special concern in 1990 when existing satellite capacity is expected to saturate.²⁸ Only limited space is available in the valuable geostationary orbit.²⁹ To enable satellites to operate without mutual interference, high performance antennas with low side lobes must be developed.³⁰ Also, higher frequencies must be used to provide additional spectral space. Finally, the information capacity of microwave frequencies already in use and of existing optical fiber systems must be increased by developing advanced microwave signal processing electronics.

Improved signal quality is needed to maintain low data error rates, especially as information capacity is increased. Improved signal quality is also needed to improve the sensitivity of microwave systems so that they can serve wider applications in communications, radar, and sensing. Such improvements will require improved fidelity in the microwave signal processing circuits for both digital and analog signals.

Expanded versatility and flexibility will also be required. They can be achieved by developing microwave systems that can operate on many different frequencies simultaneously and that can serve many different geographical areas simultaneously through electronically steered antennas.

To achieve Goal #2, of reduced size, weight, and cost of microwave components, industry must develop miniature individual components and integrated components for virtually all microwave frequencies. These components will be important for all applications but especially so for mobile, air, and space applications.

To achieve Goal #3 of improved access to the special capabilities and spectral space of higher microwave frequencies, industry must develop new electronic technologies capable of efficient performance. Both the 30-100 GHz range and the 100-1000 GHz range, where microwaves take on quasi-optical behavior, must be addressed.

²⁸1988 U.S. Industrial Outlook, International Trade Administration, U.S. Department of Commerce, p. 31-4 (1988).

²⁹The geostationary orbit lies over the equator and is about 23,000 miles high. It is the only orbit which permits satellites to revolve about the earth in such a way that they remain positioned over the same point on the earth all of the time. This "stationary" position enables them to provide continuous service to the locations beneath them. To place more satellites in this orbit, the spacing between them must be reduced, increasing the problems of mutual interference with adjacent satellites.

³⁰Antennas with low side lobes have minimal radiation off to the sides. Such antennas reduce mutual interference between adjacent satellites in orbit or between adjacent ground stations on earth.

NIST Measurement Support for Industry's Technical Goals

To support industry in pursuit of the above three technical goals, NIST will provide industry with a broad spectrum of advanced measurement capability. This measurement capability is needed to support research, development, manufacturing, marketplace transactions (including specification, performance evaluation, and procurement), installation and maintenance, voluntary industry standards for compatibility and other goals, acceptance of U.S. products in domestic and international markets, and international competitiveness broadly.

The urgency of this need has been stated in unqualified terms by U.S. industry:

U.S. industry executives have joined together under the auspices of the Institute of Electrical and Electronics Engineers to form the Committee to Promote National Microwave Standards. The Committee members, which include company chief executive officers and chairmen of the board, have issued a report stressing the urgency of the measurement needs, decrying the weakening position of the U.S. compared to its competitors, spelling out the specific measurement problems, and urging resolution of them by NBS/NIST.³¹

The National Conference of Standards Laboratories (NCSL), operating under the guidance of member representatives from major U.S. high technology companies and Government agencies, surveyed 400 organizations (346 industry, 61 government, and 4 universities) to determine key measurement needs. NCSL found a serious shortfall in NBS/NIST measurement support for microwave technology with adverse effects on major sectors of U.S. industry. The report spelled out the measurement problems and urged resolution by NBS/NIST. It also noted the negative effects of inadequate measurement support on national goals, such as productivity improvement, quality improvement, and international competitiveness, among others.³²

Industry trade articles have highlighted the urgency of the need for expanded microwave measurement support from NBS/NIST for many years.³³ For example, one article notes:

³¹The PNMS Report - Microwave Metrology in the U.S.A., Committee to Promote National Microwave Standards, an ad hoc committee sponsored by the IEEE Microwave Theory and Techniques Society (November, 1987).

³²Report by the National Measurement Requirements Committee, National Conference of Standards Laboratories, Sections 1 and 3 (Revision 2, April, 1987). The findings of the original survey were published in 1983 and were updated in the 1987 revision and again in 1989 in a report of the same name (NMRC 89-01, January, 1989).

³³Jim Fitzpatrick, "NBS and Microwave Metrology -- Growing Concern within the Industry", Microwave System News, p. 43 (May, 1984). John L. Minck, "A (Modest) Proposal to Establish a National Bureau of Microwave Standardization", Microwave System News, pp. 67-71 (May, 1986). "Metrology Funds Needed", Microwaves & RF, p. 31 (April, 1988). John Minck, "Some Significant Things That Have Happened to RF in the Last 10 Years", RF Design, pp. 29-34 (October, 1988). Ron Schneiderman, "No Funds for MMIC Metrology", Microwaves & RF, p. 76 (December, 1988).

"The NBS struggles under a woefully meager budget to research measurement technology and supply measurement services to support the measurements revolution of the '80s and the '90s. Truly an impossible task."³⁴

The measurement capability that NIST will develop to respond to these concerns can be addressed by three projects. Each project corresponds to a key group of components that requires new or improved measurement support.

Table 6
Projects of the New Microwave Program

1. Individual Components for 1-100 GHz
 - 1.1 Electronic Devices
 - 1.2 Antennas
2. Integrated Components for 1-100 GHz
 - 2.1 Integrated Electronic Circuits
 - 2.2 Integrated Antennas
3. Integrated Components for 100-1000 GHz
 - 3.1 Integrated Electronic Circuits
 - 3.2 Integrated Antennas

The order of the three projects above indicates the order in which NIST will fund measurement development if funding becomes available. Since the most immediate needs are in the 1-100 GHz range, that range will be addressed before the 100-1000 GHz range. Within the 1-100 GHz range, NIST will establish measurement capability for high performance individual components before addressing the more difficult integrated components. Here is a description of the specific work that NIST will undertake within each project.

Project 1. Individual Components for 1-100 GHz

The new measurement methods needed for individual components must embody major advances over those currently available. These advances are summarized in Table 7 and are explained more fully in the following text.

³⁴John Minck, "Some Significant Things That Have Happened to RF in the Last 10 Years", RF Design, pp. 29-34 (October, 1988).

Table 7
Measurement Advances Required for Individual Components

<u>Improvement</u>	<u>Comment</u>
higher accuracy	typically ten times greater
susceptibility to automation	manual measurement methods too slow for sophisticated new microwave systems
continuous frequency coverage	not just selected frequencies
broader interface compatibility	to support new interfaces for miniature components and new optoelectronic devices

The new measurement methods must be typically ten times more accurate to support emerging high performance systems. They must be susceptible to automation since modern systems are so complex that they cannot be efficiently characterized with today's manual measurement methods. The new measurement methods must operate over broad, continuous frequency ranges to support new systems with greater frequency flexibility; in the past, measurements at key fixed frequencies sufficed. The new methods must support a broader range of interfaces for two reasons: new miniature microwave components, with new types of interfaces, are being introduced to cut the size, cost, and weight of microwave systems; and new optoelectronic devices will be interfaced with microwave devices. For example, optical fibers will likely replace metal waveguides in key roles in satellites and antennas. The fibers are lightweight, low cost, and flexible and do not interfere with microwave beams. They may serve as signal interconnections within satellites or as controlling lines within powerful phased array antennas, among other applications.³⁵

The individual components that require improved measurement support may be divided into two groups: (1) electronic devices that generate, process, and transport microwaves without radiating them, such as signal sources, amplifiers, detectors, waveguides, coaxial cable, and connectors; and (2) antennas that transmit and receive the microwaves. The measurement needs of these two classes of components are described below.

1.1 Electronic devices

NIST will develop new measurement methods for determining critical microwave quantities in individual electronic devices. The most critical measurement needs correspond to the two

³⁵Phased array antennas contain many radiating elements. By controlling the strength and phase of the signal emitted by each element, the array can be made to produce diverse and well controlled radiation patterns to serve special needs. For example, phased array antennas can be designed to illuminate receiving areas of diverse shapes; or to reduce of unwanted side lobes (radiation off to the side of the antenna) that could interfere with adjacent microwave systems. The "phase" of an element determines the moment at which the alternating microwave signal fed to it goes through its maximum value, relative to the corresponding moments for the signals fed to the other elements.

functions that a microwave system must perform to convey information from one location to another: (1) transfer microwave power efficiently, and (2) preserve signal fidelity while doing so. In addition, improved measurement methods and reference data are required for the microwave properties of materials. The quantities of importance are shown in Table 8.

Table 8
Measurements for Electronic Devices for 1-100 GHz

<u>Measured Quantity</u>	<u>Description</u>
Power transfer measurements	
power	determines power levels throughout a microwave system
impedance	enables components to be interconnected compatibly, with minimum power loss
attenuation	determines power loss within a component
Signal fidelity measurements	
noise	enables minimizing electronic noise to optimize information throughput and to reduce errors in transferring data in a microwave system
waveshape	enables evaluating signal quality throughout a system and determining performance of signal sources, amplifiers, modulators, detectors, and electronic switching devices
Materials measurements and data	
permittivity	determines the electrical properties of the materials
permeability	determines the magnetic properties of the materials
uniformity	determines the degree of uniformity (homogeneity) of materials properties throughout the material
anisotropy	determines the degree of uniformity of materials properties as a function of angular orientation

Noise measurements serve as an example of the problems currently faced by industry. Noise is the single most important characteristic of microwave amplifiers and amplifying components (transistors); premiums are charged and paid for good noise performance. Noise performance affects the sensitivity and information capacity of systems. Yet present noise measurement capability is not adequate to characterize the noise performance currently being achieved in modern products, so manufacturers and buyers cope constantly with inadequate tools for product development, specification, and evaluation. As a result, manufacturers have repeatedly sought NIST assistance in resolving this problem. In response, NIST will develop methods for measuring noise that are far better than those currently available and that are suitable for adoption as standard methods industry wide.

Materials are important because the performance of microwave components is very sensitive to the microwave properties of the materials of which they are made. That sensitivity is particularly important in the design of the "substrates" (similar to the circuit boards of conventional electronics) that provide the waveguide channels that interconnect individual microwave electronic components. Unfortunately, most existing data on the microwave properties of materials are based on measurements made many years ago on conventional materials at frequencies below 10 GHz. Few data exist for frequencies above 10 GHz, and practically no data exist for newer materials.³⁶

1.2 Antennas

For antennas, NIST will develop measurement methods that can provide greater accuracy, improved susceptibility to automation, broader frequency coverage, and better control of the radiation pattern of antennas. Such measurement capability will enable antennas to deliver stronger signals to receiving stations, to work in close proximity to other antennas without mutual interference, and to serve applications requiring greater sensitivity and versatility. The phased array antenna is a key example of the type of powerful modern antenna requiring improved measurement support.

The measurements required fall into two classes: (1) performance measurements, and (2) materials measurements. The new program will address performance measurements for 26-100 GHz³⁷ and materials measurements for 1-100 GHz. The specific measurement quantities that will be addressed are shown in Table 9. Descriptions are provided only for those quantities not already described above.

The work on materials measurements would emphasize materials used for protective covers (radomes) for the antennas. The microwave properties of these materials are not well understood, particularly above 10 GHz, yet those properties significantly affect the performance of antennas.

³⁶NIST surveyed industry's measurement requirements for microwave materials and described the urgent needs in its "Summary Report on Measurements and Standards Requirements for Materials Used in Electromagnetic Applications: Results of a Limited Survey" (February, 1985). Materials measurements affect everything from substrates, to protective antenna covers (radomes), to microwave integrated circuits. For example, better materials measurements are essential to the success of the automated design and manufacturing processes that produce microwave integrated circuits; these circuits, in turn, can cut the cost of microwave electronics by factors up to 100.

³⁷Development of measurements for antennas (non-integrated) below 26 GHz is supported by existing NIST resources.

Table 9
Measurements for Antennas for 1-100 GHz

<u>Measured Quantity</u>	<u>Description</u>
Performance measurements	
gain	determines how successfully an antenna can focus its power in the forward direction, toward the intended receiving antenna
pattern	determines focusing performance of an antenna in all directions, essential for illuminating the desired receiving area and for reducing stray radiation that can interfere with adjacent systems
strength	determines strength of the microwave beam from a transmitting system
polarization	determines a special property of an antenna that allows it to send two non-interfering signals on the same frequency to double information handling capacity
bore sight	determines how accurately an antenna radiates in the expected direction
natural signal source characterization	
	enables use of the sun, moon, key planets, and stars as natural signal source standards for evaluating and maintaining the performance of earth terminals and satellite microwave systems while in service
Materials measurements and data	
permittivity permeability uniformity anisotropy transmissivity	determines how well the material passes microwave power
reflectivity	determines the amount of microwave power reflected by the material

Project 2. Integrated Components for 1-100 GHz

Increasingly, microwave systems will be built in integrated form to reduce size, weight, and cost. Integration will take two principal forms:

Integrated electronic circuits: integration of microwave electronic devices, like signal sources and waveguides, onto a common substrate along with associated optoelectronic devices

Integrated antennas: integration of the elements of an antenna onto a common substrate along with associated electronic and optoelectronic devices

Integration poses difficult measurement challenges for several reasons:

Minimal measurement ports: Input and output ports of electronic devices within integrated circuits are not readily accessible. In individual components those input and output ports provided convenient locations for attaching measurement devices.

Measurement probe sensitivity: Circuit elements are closer to each other, so measurement probes are more likely to disturb the circuits that they measure.

Materials sensitivity: The performance of circuits made in integrated form is even more sensitive to materials properties than the performance of circuits made from individual components.

Multiple technologies and interfaces: The incorporation of optoelectronic technology in microwave integrated circuits and antennas leads to an especially complex mix of technologies and interfaces.

These differences necessitate new definitions for measured quantities, new measurement methods, and new physical standards to support those measurement methods.

2.1 Integrated Electronic Circuits

The integration of microwave electronic devices is pursued for reasons similar to those that motivated the integration of conventional semiconductor devices. However, the structures required, the materials employed, and the types of devices used all differ. Also, microwave integrated circuits operate at 1000 times the frequency of most semiconductor integrated circuits (GHz versus MHz), making the performance of the microwave circuits much more difficult to measure. In particular, they are much more sensitive to the presence of measurement probes.

To date, the lack of measurement methods suitable for microwave integrated circuits has hampered the design of integrated circuits and the development of fabrication processes for making them. Measurement problems in microwave integrated circuits are so critical that major manufacturers estimate that 80-90% of the cost of the resulting devices is associated with testing. In some cases, manufacturers are finding that they cannot produce highly

complex microwave integrated circuits that meet all of their performance specifications with high yield.³⁸

There are four classes of measurements that must be developed to support microwave integrated circuits. They can best be distinguished by the locations at which the measurements are made:

- (1) Inside devices: measurements internal to the electronic devices within the integrated circuits, to support their design and fabrication
- (2) Input/output ports of devices: measurements at the input and output ports of the electronic devices within integrated circuits, to determine the overall performance of the devices and to establish how well they transfer microwave signals to interconnecting waveguide channels
- (3) Inside waveguide channels: measurements to determine the performance of the interconnecting waveguide channels themselves
- (4) Inside materials: measurements to characterize the microwave properties of the substrates and other starting materials used to make both the electronic devices and the waveguide channels within the integrated circuits.

Measurement development for category (1) will be adequately supported by NIST's new semiconductor program, described in Chapter 2, if all phases of that program are funded. Measurements for categories (2), (3), and (4) will require support from this new microwave program.

For categories (2) and (3), NIST will develop new measurements for the quantities shown in Table 10. For category (4), NIST will develop measurement methods, reference data, and supporting physical standards for the materials quantities shown in Table 10.

Nearly all of these quantities are important to individual electronic components, too; but the measurement methods required for integrated circuits are entirely different. Because of the small scale of integrated circuits and the proximity of all of their components, special measurement methods will be required to access the internal workings of the integrated circuits and to prevent interference with their operation during the measurement process. If some interference occurs, it must be minimized. Corrections for any remaining interference must be made based on theoretical calculations. Special contacting electrical measurement techniques and non-contacting optical measurement techniques must be developed to accomplish these aims. Also, special test structures must be developed that can be built right into commercial integrated circuits to facilitate measurement.

³⁸Jeff D. Montgomery, "Hybrid MIC North American Markets", Microwave Journal, p. 32 (April, 1989).

Table 10
Measurements for Integrated Electronic Circuits for 1-100 GHz

Measured Quantity

Power transfer measurements

power
impedance
attenuation

Signal fidelity measurements

waveshape
noise

Materials measurements and data

permittivity
permeability
uniformity
anisotropy
transmissivity
reflectivity

Lack of data on the microwave properties of materials is severely impairing the design and manufacture of integrated circuits. Such data are essential for systems used in automated manufacturing and computer-aided design since these systems depend on materials of known and uniform properties. As noted above, most existing data on the microwave properties of materials are based on measurements made many years ago on conventional materials at frequencies below 10 GHz. Few data exist for frequencies above 10 GHz, and practically no data exist for newer materials.

The materials properties of interest must be measured as a function of temperature and humidity to simulate true conditions when in use. They must be measured as a function of composition to support design and manufacturing processes. They must be measured as a function of frequency to support wideband (frequency flexible) applications.

2.2 Integrated Antennas

Integrated antennas are one of the most promising of emerging microwave technologies. They are panels, either flat or curved, which contain embedded metallic radiating elements that look much like the wiring patterns in integrated circuits. Integrated antennas may contain thousands of elements, especially when configured as phased array antennas.³⁹

³⁹The integrated phased array will be a powerful type of antenna. Its radiation pattern and direction of radiation will be electronically controlled, without physical motion of the antenna. The control is accomplished

Integrated antennas can be very large (many meters in size) or very small (a few centimeters in diameter, fabricated directly on the surface of a single semiconductor wafer). Integrated antennas will contain electronic devices built right into them. These devices will serve as small transmitters and receivers. Each transmitter or receiver may be associated with individual radiating elements or with groups of elements within the antenna. The elements in an integrated antenna may be controlled by optoelectronic devices.⁴⁰ The elements may contain built-in signal processing circuits.⁴¹ Some new antenna designs are so complicated that they cannot be economically constructed without integration.⁴²

Integrated antennas offer several advantages over conventional antennas:

Reduced size, cost, and weight: Embedding the elements in an insulating substrate reduces the structural complexity of an antenna considerably.

Adaptable shapes: Integrated antennas can be shaped to conform to the skin of a vehicle, such as an airplane, satellite, or spacecraft, and thus can meet the special aerodynamic and structural requirements of those vehicles. They can also be shaped to conform to the surfaces of buildings for aesthetic or practical reasons.

Sophisticated designs: Integrated antennas can be implemented as phased arrays, the most versatile of emerging antenna types. Phased arrays can transmit in many directions without being physically moved (electronic steering). Both the direction of transmission and the shape of the radiation pattern can be changed virtually instantly. This capability enables a single satellite with such an antenna to serve many different geographical regions on a time-shared basis by sending its signal to one location after another in rapid succession.

Integrated antennas can be driven by multiple small low power transmitters, built right into them. They do not require the traditional single high power transmitter. The use of multiple

by adjusting the strength and phase of the signal radiated by each element within the antenna. In some configurations, each element of the antenna will have its own transmitter and receiver. In other configurations, each element will have its own phase shifter but will share its receiver or transmitter with several other elements. In still other configurations, groups of elements will have a single phase shifter; and many groups, or even all groups, will share a common transmitter or receiver.

⁴⁰Optical waveguides embedded in a phased array integrated antenna may be used to control the relative strengths and phases of the signals transmitted by the individual elements of the antenna. Relative to metallic waveguides, which would otherwise be used for such control, the optical waveguides are lighter and will not interfere as much with the radiation pattern of the antenna.

⁴¹For example, the information received by each element of an integrated receiving antenna may be converted to digital form by its own semiconductor electronics, located right at the antenna element. The resulting digital data from each antenna element can then be brought out of the antenna on light beams carried by optical waveguides. This approach results in a much lighter antenna than possible when microwave signals themselves must be brought out through multiple metallic waveguides.

⁴²The individual faces of an active array may contain as many as 5000 active transmit/receive devices, and thus active arrays may not be practical to implement in any form other than an integrated form.

transmitters eliminates the need for a complex network of microwave waveguides within the antenna to carry microwave power to the antenna elements from a central transmitter. The result is a considerable reduction in weight. Also, because the transmitters for the individual elements are low power, they can employ low cost semiconductor signal sources, rather than the expensive and often short-lived microwave tubes that are required by high power central transmitters. Integrated antennas may be controlled with optical signals fed through optical waveguides. Optical waveguides are desirable because they are non-interfering; thousands of such signals will be required to control a complex integrated antenna.

To support integrated antennas, NIST will develop measurements for overall antenna performance and for the performance and interaction of individual antenna elements within integrated antennas. NIST will also develop measurement methods and reference data for the materials from which antennas are made. The quantities of importance are shown in Table 11. The new measurement approaches required will be especially challenging for several reasons:

No single input/output port: Integrated antennas do not have a single point of microwave power input or output which can provide a reference for measurements. New definitions for quantities such as gain and noise will be necessary, along with new measurement approaches.

Different transmit/receive performance: Integrated antennas will not perform exactly the same way in transmission and in reception, as conventional antennas do; so separate measurements must be made for each of these modes. The differences arise from the fact that different built-in electronics will be activated for reception versus transmission. Also, in some cases, different radiating elements within the antenna will be used for each mode.

Large size: Integrated antennas will often be physically large. They will also often be "electrically large". That is, they will be large relative to the wavelength (the distance from one ripple to another in a traveling microwave beam). Because of these "large" sizes, NIST will need to develop new measurement methods for pattern. These new methods must enable present-day antenna measurement ranges to cope with antennas that are far too complex for use of traditional measurement approaches. So called quasi-far-field measurement techniques will be required.

Element interactions: Integrated antennas are composed of many elements, so the interactions among these elements will greatly affect performance and will require a variety of measurements sensitive to the relationships among them.

As with integrated circuits, materials measurements and data will be very important. Materials properties must be measured as a function of temperature and humidity to simulate the environment in which they will be used. They must be measured as a function of composition to support design and manufacturing processes. They must be measured as a function of frequency to support wideband applications.

Table 11
Measurements for Integrated Antennas for 1-100 GHz

<u>Measured Quantity</u>	<u>Description</u>
Overall performance measurements	
gain	
pattern	
polarization	
bore sight	
noise	determines the noise contributed by the integrated antenna which now contains the transmission and reception electronics and must be evaluated as a whole
Antenna element measurements	
diagnostics	determines which elements of the antenna are not working correctly
coupling	determines the effects of the coupling between closely spaced elements on antenna performance
phase	determines how the signals from the individual elements track in relation to each other
strength	determines how well the strengths of the signals from the individual elements track with each other.
Materials measurements and data	
permittivity	
permeability	
uniformity	
anisotropy	
transmissivity	
reflectivity	

Project 3. Integrated Components for 100-1000 GHz

New measurement capability must be developed for the 100-1000 GHz region. This capability is needed to support the efforts of U.S. industry to develop equipment that will take advantage of the frequency space and special properties of the higher frequencies. Particularly attractive are the prospects for smaller antennas, higher resolution for local radar, greater versatility for local communications systems, and ultrafast speeds for signal processing.

Most of the needed work will focus on integrated components, so they are the focus of the subsections that follow. However, some measurement development for individual components will also be needed.

3.1 Integrated Electronic Circuits

The key parameters that must be measured are the same as those specified for the 1-100 GHz range in section 2.1, but different measurement methods will be required. The differences are caused by the following factors:

Quasi-optical behavior: The frequencies in the 100-1000 GHz range, particularly at the high end, take on the behavior of light, giving rise to new materials problems, new requirements for component designs, and higher levels interface complexity.

Smaller geometries: The characteristic sizes of circuit elements will be smaller at these frequencies.

Higher sensitivity to measurement probes: The sensitivity of integrated circuits to the presence of measurement probes will be greater at these frequencies.

Higher sensitivity to materials properties: The sensitivity of integrated circuits to materials properties will be greater at these frequencies.

In this 100-1000 GHz domain of frequency, development of non-contacting optical methods, rather than contacting electrical methods, for measuring microwave parameters within integrated circuits will be especially important to prevent disturbing the circuits being measured.

The full spectrum of materials properties cited for the range of 1-100 GHz in section 2.1 must be addressed for this new frequency range of 100-1000 GHz where the properties will differ considerably.

Measurements supportive of microwave signal processing electronics will be especially important to realize the promise that they offer for extraordinary processing speeds.

3.2 Integrated Antennas

Measurement development for antennas will focus initially on the domain of 100-300 GHz and later on the domain of 300-1000 GHz. As in category 3.1 above, special measurement methods will be needed to cope with quasi-optical behavior, smaller geometries, and higher sensitivity to measurement probes and to materials properties. In addition, measurements for coupling among antenna elements, and between these elements and other circuit elements, will prove very important and challenging at these frequencies.

Development of measurement support for the range of 100-1000 GHz will assure that U.S. industry has both the measurement methods and the materials data that it needs to accelerate its research and development efforts toward the next generation of high frequency microwave products.

Chapter 9
VIDEO TECHNOLOGY
Phase 1 of New Program Plan

Summary

Video technology, to date, has not been able to take advantage of the ability of human vision to see both high resolution images and smooth motion at the same time. Computers have focused on high resolution to permit clear display of text at the expense of smooth motion. Television has focused on smooth motion at the expense of clear display of text. Now advances in five key technologies that support video technology promise both capabilities in a single video system. As a result, the services of computers, televisions, and telecommunications systems can be merged into a powerful new video "window" to the information age. This merger will provide new capabilities for such diverse applications as education, entertainment, medicine, defense, security, transportation, publishing, advertising, and banking. Advanced video technology will serve business and government broadly through improved office automation, electronic mail, and teleconferencing. If the prospect of on-demand services through networks can be added, users will gain access to libraries of text, audio, and video information whenever they wish.

The five emerging technologies that will bring these capabilities to video systems are these: (1) high resolution vision systems that capture high quality video images; (2) real time signal processing systems that prepare video images for transmission, storage, and display; (3) high data rate transmission systems, including optical fiber and microwave communications systems, that transmit video images; (4) high density information storage systems that record and store video images; and (5) high resolution displays that reproduce high quality video images.

The expanded markets that advanced video systems will create for the products of these five technologies are vast. Already, present world markets for the products of these technologies are in the range of \$100-200 billion dollars per year. Even modest percentage increases attributable to advanced video technology will yield enormous markets.

International competition to meet the demand for advanced video systems is intense. The winners in this international competition will penetrate markets of high diversity. At the present time, the development of advanced video technology is dominated by Japan, with Europe a close second. Japan has already broadcast high definition television programs, a major application of advanced video technology, on a trial basis during the Seoul Olympic Games. Europe plans high definition television broadcasts of the 1992 Olympic Games. The U.S. is a lesser player in the development of advanced video technology, but the U.S. will certainly be a major consumer.

Whether the U.S. decides to compete in the development of advanced video technology or just to consume that technology intelligently, it will need new measurement capability. That measurement capability will support research, development, manufacturing, marketing, and use of advanced video technology. The new measurement capability will enable evaluation of candidate components and technologies for advanced video systems, whether for development or for purchase, and thus will accelerate the selection processes that both manufacturers and users of advanced video technology must go through.

NIST is uniquely positioned to help U.S. manufacturers and users. NIST's measurement competence, plus its impartial position relative to buyers, sellers, and regulators, will enable it to work with all parties in providing needed measurement capability. NIST's close working relationship with U.S. industry will enable early identification of industry's measurement problems and rapid transfer of solutions. NIST's depth and breadth in measurement capability will help it cope with the high performance levels and broad range of supporting technologies on which advanced video technology depends.

NIST's proposed program would be conducted in phases. Phase 1 provides for the development of selected measurement methods needed for three of the five supporting technologies: real time signal processing, high data rate transmission, and high density information storage. Phase 1 is the subject of this document. Later phases will address additional measurement requirements of these three technologies plus the first measurement requirements of the remaining two supporting technologies: high resolution vision systems and high resolution displays.

Phase 1 will include a special focus on development of measurement methods for digital techniques for advanced video systems. Digital techniques may be used alone or in combination with analog techniques in advanced video systems. They can serve one or more of three key functions in advanced video technology: signal processing, transmission, and recording. Digital techniques enable detailed processing of video signals for diverse purposes (e.g., data compression, noise reduction, and special effects). Digital techniques also enable storage and transmission of video information with high resistance to degradation of picture quality.

In particular, NIST will do the following in Phase 1. For real time signal processing, NIST will develop measurement methods for evaluating data compression algorithms and data converters. For high data rate transmission, NIST will provide test methods for evaluating high speed network protocols which control the operation of cable systems. For high density information storage, NIST will develop measurement methods needed to improve the density of stored information in magnetic storage devices for advanced video systems. Finally, NIST will create an advanced video test facility to support evaluation of key components of video systems and to foster intensive interaction with industry.

In other new programs that will be coordinated with this one, NIST will develop measurement methods for the components and transmission technologies required by microwave and optical fiber transmission systems broadly; these measurement methods are required both for advanced video applications and for many other applications.

Organization of This Document

Description of Advanced Video Technology
Alternatives for Implementing Advanced Video Technology
Demands of Alternatives on Five Supporting Technologies
World Market and International Competition
NIST's Role
NIST's Plan for Measurement Support

This document begins with a description of advanced video technology. It continues with a discussion of the various technical alternatives for implementing advanced video technology and the technical advantages and disadvantages of those alternatives. An assessment is then provided of the technical demands that these alternatives place on five supporting technologies. It is these demands that give rise to the measurement needs that NIST proposes addressing in the last section of the document.

The significance of the world markets and of U.S. international competition in the five supporting technologies is discussed, as is NIST's role in resolving the measurement problems that bear on that competitive position. Finally, NIST's plan for resolving a first set of measurement problems is described.

Description of Advanced Video Technology

The term "advanced video technology", as used here, refers to the generation, processing, storage, transmission, and display of video images with the high resolution required for clear presentation of publication-grade text and with the high speed required for smooth motion. In its most futuristic form, advanced video technology would be implemented with networking to interconnect multiple users, potentially on an international scale, and with access to on-demand services that provide video, audio, text, and data.

Advanced video technology is a powerful tool of the information age. Its power comes in large measure from its attempt to take full advantage of capabilities of the human eye, the most effective sense for taking in information.

Advanced video technology is also one of the most demanding technologies that the world has attempted to commercialize. It requires sophisticated, high performance, and reliable electronic and optical components and networking strategies. All of these must be implemented at affordable cost.

Advanced video technology will serve so many fields in so many ways that the potential impact is difficult to assess. At a minimum, advanced video technology will serve the specific fields of education, entertainment, medicine, defense, security, transportation, publishing, advertising, and banking. More generally, advanced video technology will serve business and government broadly through improved office automation, electronic mail, and teleconferencing.

Here are some specific examples of the services that advanced video technology could provide. In education, individuals could gain access through networks to giant libraries of information

in text, audio, and video form. They could read text, hear music, and see still or moving pictures of historical events. In entertainment, high resolution video programming accompanied, by superb sound quality, would become available (high definition television). In medicine, consultation with medical experts at distant locations would be furthered by pictures of outstanding clarity and color accuracy for surgical procedures, live sonogram or x-ray images, etc. In business and government generally, high performance and widely available teleconferencing capabilities -- as common as the telephone today -- could further collaborative efforts and foster creativity among individuals working across great distances. In domestic lives, families members at different locations could share holiday events through giant flat screen displays and superb sound systems that truly are the next best thing to being there. In personal and business lives, individuals could gain immediate electronic access to the day's newspapers, displayed with sharp text and color pictures, including newsreels, all easily searchable for topics of interest by busy people, and with no waste of trees, disposal space, or gasoline for the use and hauling of paper copy.

Such new services will require high levels of information handling capacity, provided at affordable cost. Advanced video systems will demand more information capacity than any other products yet contemplated for broad use in both commercial and consumer markets.

Alternatives for Implementing Advanced Video Systems

Advanced video systems can be implemented in a variety of ways. The alternative approaches are not necessarily mutually exclusive. They may serve different applications or accommodate different goals in capability, compatibility, or cost. The alternatives are summarized in Table 1 and are discussed in the following sections, along with their advantages and disadvantages.

Compatibility

Compatibility has at least two dimensions: compatibility among advanced video systems, and compatibility between advanced video systems and present television.

Compatibility among advanced video systems offers several advantages. It reduces the cost of the systems by providing high commonality of components. It furthers efficient use of advanced video systems by enabling them to serve in multiple applications. It increases the chances that new systems will eventually be interfaced with each other through a common network, further broadening applications. Compatibility has the disadvantage that it may lead to the production of some systems with more or less capability than needed for some applications.

Compatibility between advanced video systems and conventional television would enable utilization of the enormous installed base of television sets in the U.S. "Ninety-five percent of U.S. households currently own a color TV", and "twenty million new color TVs were sold to retailers last year, an all-time record".¹ The Federal Communications Commission has

¹The U.S. Consumer Electronics Industry: 1989 Annual Review, Consumer Electronics Group, Electronic Industries Association, p. 20 (1989).

already taken steps to assure that programs broadcast over the air using advanced video technology will be accessible to present television sets, either through compatible implementations of advanced video technology, or through simultaneous broadcast of advanced and present formats.²

Table 1
Alternatives for Implementing Advanced Video Systems

<u>Issue</u>	<u>Alternatives</u>	
compatibility	among advanced video systems, with TV, or both	
encoding	analog, digital, or a combination	
picture quality	continuum of choices	
compression	degree of compression	
transmission method	<div style="display: inline-block; vertical-align: middle; border-left: 1px solid black; border-right: 1px solid black; padding: 0 5px;"> broadcast (one-way) </div>	<div style="display: inline-block; vertical-align: middle; border-left: 1px solid black; border-right: 1px solid black; padding: 0 5px;"> air terrestrial satellite </div>
		<div style="display: inline-block; vertical-align: middle; border-left: 1px solid black; border-right: 1px solid black; padding: 0 5px;"> cable coax optical fiber </div>
	<div style="display: inline-block; vertical-align: middle; border-left: 1px solid black; border-right: 1px solid black; padding: 0 5px;"> network (two-way) </div>	<div style="display: inline-block; vertical-align: middle; border-left: 1px solid black; border-right: 1px solid black; padding: 0 5px;"> cable coax optical fiber </div>
storage method	magnetic, optical	
display technology	cathode ray tubes flat screen	<div style="display: inline-block; vertical-align: middle; border-left: 1px solid black; border-right: 1px solid black; padding: 0 5px;"> liquid crystal vacuum fluorescent plasma gas discharge light-emitting diodes electroluminescent vacuum microelectronic </div>

Encoding

Encoding refers to the method used to prepare information for transmission and storage. Present television pictures are transmitted and stored with analog encoding. Analog encoding is accomplished by varying the transmitted or stored video signal smoothly in response to the brightness and color levels of a picture.

²Tentative Decision and Further Notice of Inquiry ... in the matter of Advanced Television Systems and Their Impact on the Existing Television Broadcast Service", FCC 88-288 37462, Federal Communications Commission, pp. 5-6 (September 1, 1988).

An alternative scheme is digital encoding. Digital encoding means converting the analog information signal into a series of numbers like those computers use. The numbers are stored or transmitted to a desired receiving location. When received, or recovered from storage, the numbers are used to reconstruct the original analog information signal.

Digital encoding has a number of advantages. It enables reconstruction of the original signal with a predetermined level of quality, even in the face of considerable degradation during transmission and storage. That degradation may take the form of signal strength, introduction of noise, introduction of distortion, or other effects. Digital encoding also enables processing information signals in powerful ways. Finally, digital systems are directly compatible with computer data, so computer data require no conversion processes.

Digital encoding has disadvantages, too. The fastest digital circuits are not as fast as the fastest analog circuits and cost more for a given speed. Therefore, the use of digital encoding raises the cost of a system, and, if major speed advances are required, can delay implementation. Also, digitally encoded signals generally require more transmission capacity or storage capacity than their analog counterparts.

A third alternative is a combination of analog and digital encoding. Such combinations can reduce the total amount of digital information that must be processed and can facilitate achieving compatibility with present analog systems. Note that some digital techniques are used in present day television receivers to provide performance enhancements.

Picture Quality

Picture quality is determined by a number of factors: (1) the number of lines in the picture; (2) the number of identifiable picture elements (pixels) in each line; (3) the number of brightness levels for each color for each pixel; (4) the number of pictures created per second; (5) and the "scanning" technique used to create and send each picture. A scanning technique is required because all video pictures are sent line by line. That is, the information across the area of the picture must be reduced to a steady stream, or line, of data before it can be sent. In progressive scanning, every line of a picture is sent in succession. In interlaced scanning, all odd-numbered lines are sent in succession, followed by all even-numbered lines. Progressive scanning produces the highest quality picture. Interlaced scanning does almost as well and enables reducing the data rate required by a factor of two. The factor of two results from the fact that in interlaced scanning, one set of alternate lines is sent in the same time interval used to send an entire picture in progressive scanning.

A combination of all of the above factors determines the amount of information that must be transferred to send a picture and thus determines the quality of the picture. The picture quality for advanced video systems can be selected from a continuum of possibilities. Improvements of factors of two to more than ten, relative to present television, are generally discussed for various implementations. A factor of ten will be assumed as the basis for the rest of the discussion in this document. A factor of ten improvement would mean that a digitally encoded advanced video signal would contain about 1 gigabit per second (10^9 bits per second) of information. In comparison, a conventional television signal, if encoded in digital

form rather than its usual analog form, would require about 100 megabits per second (10^8 bits per second).³

Compression

The large amount of information required to produce high quality pictures is particularly difficult to accommodate during transmission and storage. For this reason, considerable thought is being given to methods of reducing the amount of information that must be transmitted or stored to achieve a picture with a given level of "perceived" quality. By taking advantage of the characteristics of human vision when viewing moving images, considerable reduction, or compression, is possible. Compression is done before storage or before transmission; and the complementary process, decompression, is done after playback from storage or after reception, respectively.

Compression techniques may be used with both analog and digital encoding. Interlaced scanning is an example of an analog compression technique. Several other analog compression techniques are used in present day television broadcasting and could be used also with advanced video systems. Digital encoding enables a broad diversity of compression techniques to be implemented by computers. For example, one simple method of compression that can be used in digital systems is to send a full picture only 6 times a second, instead of the usual 30 times a second. Then, at the receiving end, a computer creates, by calculation from each adjacent pair of pictures, four intermediate pictures that make a smooth transition between the original pair. Using more sophisticated techniques, compression by a factor of about seven or eight should be possible without significant degradation of picture quality.

Compression techniques have disadvantages, too. They can increase the cost of the receivers by requiring them to have complex signal processing circuits to decompress the incoming signal. Also, highly compressed video data is highly sensitive to errors introduced by transmission or storage. Tolerable error rates may be limited to 1 bit wrong out of every 10^{10} to 10^{11} transmitted or stored.⁴ This is about 10 to 100 times more demanding performance than the raw performance of most networking hardware used with computers. Such hardware is usually designed for an error rate no greater than 1 bit in 10^9 .⁵ In contrast, uncompressed video data is relatively insensitive to errors.

Compression is not unique to video systems. It is already used for FAX machines, teleconferencing, robot vision, and speech. For modern digital speech systems, such as those in new digital telephone lines, compression can enable reduction of speech data requirements from 64 to 8 kilobits per second, or even less with loss of some naturalness. Data

³Dennis Roddy and John Coolen, Electronic Communications: Third Edition, p. 600 (1984).

⁴Hitomi Murakami, Hideo Hashimoto, and Yoshinori Hatori, "Quality of Band-Compressed TV Services", IEEE Communications, pp. 65 (October, 1988).

⁵These error rates are those provided by the basic transmission hardware, prior to the execution of software programs that correct errors. These software programs are highly sophisticated and can reduce the errors to insignificance at the expense of additional computing time and slowed throughput.

compression will become an important tool in future low speed video applications including security where it will aid in passport and fingerprint storage, retrieval, and identification.

Transmission Method

Advanced video systems may employ one or more of a number of transmission alternatives. Some of these are broadcast, or one-way, methods; others are network, or two-way, methods. The broadcast alternatives are summarized in Table 2. They are arranged in order of increasing information handling capacity. That capacity increases with the frequency of operation of the transmission method.

Table 2
Broadcast Transmission Alternatives

<u>Transmission method</u>	<u>Frequency of operation</u>
terrestrial broadcast	submicrowave frequencies (below 1 gigahertz)
coaxial cable	submicrowave frequencies (below 1 gigahertz)
direct broadcast satellite	microwave frequencies (above 10 gigahertz)
optical fiber cable	optical frequencies (200,000 gigahertz)

Among the broadcast alternatives, one approach is to transmit over the air. Transmission may be accomplished by terrestrial broadcast systems, like those used for present television, operating at frequencies below 1 gigahertz. Or transmission may be accomplished by direct broadcast satellites, operating at frequencies above 10 gigahertz.

Terrestrial broadcasts, the first over-the-air broadcast approach, have some key advantages. They offer the prospect of compatibility with present television. They also operate on relatively low frequencies (below 1 gigahertz) for which receiver electronics are relatively inexpensive. Terrestrial broadcasts have disadvantages, too. They have limited information capacity because of their relatively low frequency of operation. Further, they cannot operate on frequencies much above 1 gigahertz because those frequencies do not propagate well along the surface of the earth. Since the broadcast of advanced video technology will require more information capacity than present television, the number of available channels will have to be reduced. The tradeoff between the number of channels and performance is a complex one.

Direct broadcast satellites, the second over-the-air broadcast approach, operate somewhat differently. The satellites are positioned in the "geosynchronous orbit" above the equator where they orbit exactly with the rotation of the earth. Thus they remain over the same locations always. They send signals directly to the antennas of individual recipients, along a line of sight. Such satellites for advanced video technology will likely operate at frequencies above 10 gigahertz, for two reasons: these frequencies offer high information carrying capacity; they also work well with small antennas.

Direct broadcast satellites have the advantage that they are relatively easy to implement; a single satellite can serve a huge geographical area, even the entire United States. They are also readily reconfigurable; that is, they can be redirected to serve different areas, especially

if they are equipped with electronically steerable antennas (antennas that can be directed by electronic commands alone, without physical movement). Direct broadcast satellites have disadvantages, too. The receiving equipment that individual users must have is expensive. The high cost is attributable in part to the high frequency of operation and in part to the high sensitivity required to pull in relatively weak satellite signals from high satellite orbits (22,000 miles out). Much less sensitivity is needed to receive more powerful terrestrial broadcast stations from distances of only a few tens of miles.

The basic concept of direct broadcast satellites is not novel, even if the performance levels required for advanced video systems are extremely high. The U.S. presently uses satellites to deliver television programs to local television stations for terrestrial rebroadcast. Those transmissions can be received directly by users in a manner entirely similar to direct broadcast satellites. In fact, 1.5 million such receivers are already in use in the U.S., particularly in rural areas with limited access to terrestrial broadcast stations or cable television.⁶

Broadcasting can also be accomplished over cable, either coaxial cable, which is employed by present cable television systems, or optical fiber cable. Coaxial cable is capable of delivering advanced video signals. However, cable is limited to operation at low frequencies, typically below 550 megahertz, which is equivalent to 0.550 gigahertz. Since the amount of information that a transmission system can carry increases with its frequency, coaxial cable can carry somewhat less information than alternative transmission systems operating at higher frequencies. The relatively low frequencies at which coaxial cables operate are necessary to minimize signal losses that rise rapidly with frequency. Optical fiber cable, which operates at much higher frequencies (200,000 gigahertz), offers hundreds of times lower losses, and has potentially thousands of times higher information capacity. But realization of that potential will require development of higher performance optoelectronic components that can exploit more fully the natural capacity of the fiber itself. Fiber installations are presently more expensive than coaxial installations, but this situation is expected to change as early as 1992.⁷ In fact, a Bellcore spokesman expects 5-6% of homes to be receiving fiber by 1996⁸; and market-researcher Electronicast expects about 15% of homes to be receiving fiber by 1999.⁹

Comparing the over-the-air broadcast approaches, as a group, to the cable broadcast approaches, the over-the-air approaches have the advantage that they are easier to implement, since they do not require wiring every recipient, resolving difficult right-of-way issues, or navigating difficult terrain. However, the cable approaches have advantages, too. The entire information capacity of the cable can be dedicated to a single purpose, since the cable system,

⁶The U.S. Consumer Electronics Industry: 1989 Annual Review, Consumer Electronics Group, Electronic Industries Association, p. 30 (1989).

⁷According to a Bellcore official, as noted in Television Digest, Volume 29, No. 39, p. 5 (September 25, 1989). Same year of 1992 cited as the break even point, according to "analysts", by Lois Therrien, "Fiber Optics: Getting Cheap Enough to Start Rewiring America", Business Week, p. 86 (July 31, 1989).

⁸Television Digest, Volume 29, No. 39, p. 5 (September 25, 1989).

⁹Lois Therrien, "Fiber Optics: Getting Cheap Enough to Start Rewiring America", Business Week, p. 86 (July 31, 1989).

unlike the over-the-air system, does not have to share available frequency space with highly diverse services such as FM radio, mobile radio, aircraft and satellite communications systems, police and fire services, radar systems, and many others. Also, the cable system does not require users to cope with interference or with antenna installations that must accommodate varying local terrain and distances from transmitting locations.

At the present time in the U.S., about 50% of all homes with television sets are served by cable systems.¹⁰ The rest rely solely on over-the-air broadcasts.

An alternative to the broadcast, or one-way, approach, is the networking, or two-way, approach. Networks route transmissions flexibly between arbitrary points of transmission and reception. Networks for advanced video technology require so much information handling capacity that over-the-air approaches are unlikely. They could support only very small numbers of users in the spectral space accessible with technology available in the near term. Cable approaches will likely be necessary.

Among the cable approaches, coaxial cable presents some difficulties for networking for advanced video technology because of its limited information capacity. Coaxial cable is not likely to provide adequate service to a large numbers of users in a networking environment.

Optical fiber cable, however, will be able to serve large numbers of users in advanced video networks, if high performance components that can exploit the cable's capacity fully can be developed. In fact, optical fiber cable systems should eventually be able to carry at least 1000 uncompressed advanced video signals simultaneously, and perhaps seven to eight times more compressed signals.

Storage

"Storage" here refers to long term storage rather than to momentary storage provided by semiconductor memory. Because advanced video systems produce so much information every second, storage becomes a major challenge. Information from advanced video systems may potentially be stored by either magnetic or optical storage systems with either analog or digital encoding. Storage with analog encoding is more compact than storage with digital encoding but is also more susceptible to degradation of image quality. Storage in optical form would enable writing data to, and reading data from, the storage media without physical contact with the media, thus reducing wear. But optical storage systems are presently limited in capacity by the relatively small amount of surface area that they can offer for storage on spinning disks. Storage in magnetic form on spinning disks has the same problem, but storage on magnetic tape offers much more surface area. However, use of magnetic tape requires physical contact for writing and reading data, giving rise to wear.

¹⁰The U.S. Consumer Electronics Industry: 1989 Annual Review, Consumer Electronics Group, Electronic Industries Association, p. 21 (1989).

Display Technology

Many promising alternatives are emerging for display technology. Cathode ray tubes are used in present day television sets. They produce light by scanning an electron beam (the "cathode ray") across a phosphor screen to stimulate the emission of light. They are capable of high brightness and good color reproduction. But because they are evacuated devices, they must be made from strong and heavy materials to withstand the pressure of the atmosphere. They become increasingly difficult to implement in large screen sizes. They raise some safety concerns associated with radiation. In contrast, emerging flat panel displays require considerably less size and weight for a given screen size and raise no safety concerns. They are presently more expensive than cathode ray tubes of the same screen size, but their cost is decreasing and their performance is rising. Some of the key alternative technologies for flat screen displays are listed in Table 1. Liquid crystal displays have already been made in color form.

Demands of Alternatives on the Five Supporting Technologies

The many alternative approaches to advanced video technology place heavy demands on five supporting emerging technologies:

- High Resolution Vision
- Real Time Signal Processing
- High Data Rate Transmission
- High Density Information Storage
- High Resolution Displays

Here is a description of those demands, stressing the high performance levels and new components needed to meet the requirements of advanced video technology.

High Resolution Vision

High resolution vision systems must capture the signals used for advanced video systems. The standards elected for picture quality will determine the resolution required, but ten times greater performance than available from present television can be anticipated. The vision systems referred to here are principally video cameras, but scanners that read documents (including photographs) and computers that synthesize images, including moving images, from data will also be important sources. Key among the demands placed on video cameras will be their performance with moving images, and in particular, their ability to deliver adequate levels of resolution in the presence of moving images.

Real Time Signal Processing

Most of the information sent in advanced video systems will have to be processed in "real time". That is, it must be processed as fast as it is generated so that a backlog of unprocessed information does not build up. This is obviously essential for live television, but it is also necessary for playing back recorded material which is to be viewed or listened to at natural speeds.

Real time signal processing is principally relevant to digitally encoded forms of advanced video technology, since digital techniques facilitate the manipulation of all data, including video data. If digital encoding is used, then analog-to-digital data converters will be needed at the transmission end to translate the video information into digital form. Similarly, digital-to-analog data converters will be needed at the receiving end to translate the digital data back into analog form for display. These converters may have to operate at microwave speeds (above 1 gigahertz). Analog-to-digital and digital-to-analog data converters are presently used in test equipment, such as voltmeters and oscilloscopes, and in entertainment equipment, such as audio recording equipment and audio playback equipment, including compact disk players.

If digital techniques for compression are used, then digital processors, data compression techniques, and semiconductor memories will be required. Some or all of these may have to operate at microwave speeds (above 1 gigahertz). Each of these is discussed further below.

Digital processors are the circuits that constitute the "brain" of a computer. In advanced video systems, they can be used to compress and decompress transmitted information, to correct errors, to reduce noise, or to create special effects. Digital signal processing in the studio will likely be needed for editing and special effects, whatever encoding scheme is used for transmission.

Data compression techniques are the mathematical instructions used by the processors to compress and decompress data. If advanced video information is to be stored or transmitted in compressed form, then powerful data compression techniques will be needed.

Semiconductor memories, especially dynamic random-access memories (DRAMs), are the integrated circuits that will provide momentary storage of video information while digital processors manipulate the information for compression before transmission or storage, and for decompression, error correction, noise reduction, etc. after reception or playback from storage.

High Data Rate Transmission

For implementation of broadcast approaches with either terrestrial over-the-air approaches or coaxial cable, the capabilities of existing terrestrial television broadcast systems and existing coaxial cable systems will have to be expanded to reach the required information capacity. This would most likely be accomplished by reducing the number of available channels. This approach to implementing advanced video technology probably places the fewest requirements on advances in transmission technology.

For implementation of direct broadcast satellites, high performance broadcast satellites and ground-based receiving equipment will be required, all operating at microwave frequencies and all capable of delivering signals with high information capacity. Antennas with superb control of beam shape and direction will likely be needed to enable direct broadcast satellites to concentrate their limited energy on specific geographic regions. Higher power microwave sources for satellites will also be needed to reduce the sensitivity required by the multitude of receivers. Microwave integrated circuits will be needed to reduce the cost of microwave satellite electronics and ground receiver electronics.

For implementation of fiber optic cable in broadcast mode with digital encoding, higher information capacity will be required for optical fiber communications systems. New components will be needed that can exploit the information capacity of the fibers. In particular, high performance modulators, multiplexers, switches, amplifiers, and coherent system components will be needed. Coherent systems are especially important; they will enable tuning among many channels on an optical fiber, much as present television does. Further, fiber optic lines will have to be installed for local delivery to offices and homes, not just for the cross-country and undersea routing. This requirement will create an explosive growth in the market for optical fiber system components.

For implementation of networking on fiber optic systems, high performance components will be again be required. Also needed will be protocols. Protocols are standard practices for controlling and exchanging data on the network. Protocols affect both the physical architecture and the controlling software of network systems. Ideally, these protocols should be international in scope to permit interconnecting information systems worldwide. The most significant international protocols currently under development are those for the Integrated Services Digital Network (ISDN).

The ISDN concept integrates support for text, audio, video, and computer data. Two levels of ISDN are presently the focus of international attention. Narrowband ISDN can support data rates up to 1.544 megabits per second for an individual user. Broadband ISDN can support data rates up to 622 megabits per second for an individual user. An international protocol for Narrowband ISDN was adopted by an international standards body, the International Consultative Committee for Telephone and Telegraph (CCITT), in December, 1988. An international protocol for Broadband ISDN will be voted on by the CCITT in 1992. Narrowband ISDN does not require optical fibers and will not have sufficient capacity for advanced video signals, although it can send slower video information. Broadband ISDN will employ optical fibers and will be able to accommodate two to four highly compressed advanced video signals. Variations of ISDN with even greater capacity are the subject of international research.

Other approaches to networking are also the subject of international research. One of these is the Passive Optical Network.¹¹ It provides very high information capacity for two-way communications. It works much like a two-way broadcasting system; every party on the network has the capability both to broadcast and to receive. This approach exploits the very high information capacity of optical fiber systems to reduce network complexity by simplifying switching and network protocols.

High Density Information Storage

For implementation of optical or magnetic information storage, advanced video systems will require major increases in the capacity of storage systems and in the rate at which data can be stored or played back. Capacity increases might be obtained with an increase in the amount of information stored per unit area (the information density) and/or with an increase

¹¹Peter Cochrane and Mike Brain, "Future Optical Fiber Transmission Technology and Networks", IEEE Communications Magazine, Vol. 26, No. 11, pp. 45-60 (November, 1988).

in the area used for storage. Depending on the increases obtained in density, playback-rate increases might have to be achieved by operating systems at higher mechanical speeds. For magnetic tape systems, this would mean higher rates of wear and more critical tolerances during manufacturing.

The relative importance of optical and magnetic storage systems for advanced video technology is not entirely clear at the moment. Magnetic tape is attractive because it permits major increases in area rather easily, by just using longer (if not also wider) tapes. Magnetic disks and optical disks do not lend themselves as easily to large increases in area.

Today's computer disks provide a reference point for understanding the limitations of disk-based magnetic and optical storage for systems employing digital encoding. Today's single-unit high capacity magnetic and optical storage systems for computers hold 1 to 6 gigabytes. The optical systems store about 10 times more information in a given area than the magnetic systems, but the transfer rates are about half as fast and the error rates are much higher. Thus today's computer storage systems would store only 8 to 48 seconds of advanced video information in an uncompressed format and perhaps only 1 to 6 minutes in a highly compressed format. Further, the transfer rates of typical fast digital storage systems are about 40 times too slow for advanced video applications. Generally, magnetic disks are not removable since they are highly sensitive to contamination; optical disks are removable. Clearly, the challenges facing disk storage technology in service to advanced video technology are formidable.

New storage technologies that are only in the research phase now may emerge to serve advanced video technology. One approach may be to exploit the three dimensional nature of matter to enable storing much more information than possible with the surface-based storage approaches in present use.

High Resolution Displays

The alternatives for display technology can be somewhat flexibly applied to a number of applications. Cathode ray tubes can already be made with the performance required for advanced video technology, but they are very expensive and heavy in large screen sizes. Flat panel displays are on the rise, but require much additional development. The first full color flat screen displays, made from liquid crystals, are available in the market for computers and for miniature television applications. Major challenges for flat screen displays include achieving adequate brightness levels, proper color rendering, and low cost. The displays will likely contain embedded electronic driving circuits throughout. During manufacture they present many of the problems of integrated circuits, but those problems are greatly exacerbated by the large size of the displays, which may be one to two square meters in area. Also, they are likely to require mixed technologies, combining, for example, liquid crystals with semiconductor driving circuits, all in microcircuit form.

World Market and International Competition

Proponents of advanced information technologies, like advanced video technology, predict that the information technologies will produce the same sweeping economic impact in coming years

that the railroads and interstate highways have in past years. Thus, it is not surprising that advanced video technology has been targeted for development by foreign governments and firms who wish to realize its substantial economic potential. The Japanese and the Europeans have been particularly active. The U.S. has been less so, but possesses many of the skills required to participate.

The economic impact of advanced video technology will come from at least three factors: the sale of components and equipment for advanced video technology; the sale of the services performed with the new technology; and economic stimulation within the countries exploiting those services for business and commerce.

Note that the market for components and equipment alone will be enormous. Table 3 shows estimates of the world market for components and equipment for subcategories of the five supporting technologies for which market data is available. More than \$100 billion dollars per year of components and equipment are already sold in the subcategories. Thus even small percentage increases in the market attributable to the emergence of advanced video technology will yield huge world markets. Thus it is not surprising that the world market for the equipment required for just one application of advanced video technology, high definition television, has been projected at rather large values, typically \$5 billion to \$20 billion per year at some time between 2000 and 2010.¹²

U.S. competitiveness in the technologies supporting advanced video technology varies from strong to weak in different areas. Here are some key details.

For optical fiber transmission, the Japanese are on a par with the U.S. in fiber technology and are ahead and moving farther ahead in the technology of other key components, such as sources and detectors.¹³ The Europeans are proving to be effective competitors, too. The world market for optical fiber and supporting components reached \$3.2 billion per year in 1989 and is expected to grow to \$10.8 billion per year by the year 2000, according to the Department of Commerce.¹⁴ The value of the equipment and systems constructed from these components is, of course, much higher. The installation of fiber to individual businesses and homes would assure high growth in the market for optical fiber and supporting components. In the U.S., at present, there are already isolated test applications.

¹²An even more optimistic estimate of \$28.5 billion per year is provided in "Source: Dataquest", announcing High Definition Video Technology: The Collision Between Television and Computers, Dataquest Incorporated (San Jose, California), p. 1 (1989).

¹³JTECH Panel Report on Telecommunications Technology in Japan - Final Report, Science Applications International Corporation, p. 1-21 (May, 1986). The Japanese Technology Evaluation Program (JTECH) "was initiated in 1983 by the U.S. Department of Commerce; currently the National Science Foundation is the lead supporting agency."

¹⁴International Competitiveness Study: The Fiber Optics Industry, Office of Telecommunications, International Trade Administration, U.S. Department of Commerce, p. 25 (September, 1988).

Table 3
World Market (1988 or 1989) for Present Components and Equipment

	<u>billions of dollars</u>
vision and transmission	
studio cameras	
broadcast transmission equipment	32 ¹⁵
microwave transmission equipment	
fiber optics transmission equipment	
telephone and telegraph equipment	39 ¹⁶
signal processing	
memory	11
storage	
magnetic	40
optical	2
displays	9
cathode ray tubes	
flat panel displays	—
total	133

For microwave equipment, the U.S. is not penetrating foreign markets well. For example, U.S. exports in the broad category of "radio communication and detection equipment" (SIC Code 3662), which includes microwave equipment, were only \$4.5 billion in 1988, relative to all U.S. shipments of \$54 billion. Imports were higher at \$5.0 billion, yielding a negative balance of trade. Japan supplies 48% of all U.S. imports in this category, four times the contribution of any other country. In contrast, only 9% of U.S. exports go to Japan.¹⁷ Thus, the U.S. has a lot to gain by better penetration of the world market, and a lot to lose by increased penetration of its own market. Particularly troublesome is the progress that the Japanese and Europeans are making toward development of microwave integrated circuits. These circuits promise major increases in performance per unit cost. The countries first

¹⁵U.S. shipments of communications systems and equipment, except broadcast equipment, were valued at \$12 billion dollars in 1988. U.S. shipments of broadcast equipment were valued at \$2 billion dollars in 1988. These figures come from the 1989 U.S. Industrial Outlook, International Trade Administration, U.S. Department of Commerce, p. 27-2 (1989). Thus all U.S. shipments for communications total \$14 billion in 1989. To estimate world shipments from U.S. shipments, a multiplier of about 2.1 to 2.5 is usually about right for high technology electronics fields. If the value of 2.3 is used as a mean, then world shipments of communications products would be about \$32 billion for 1988.

¹⁶U.S. shipments of telephone and telegraph equipment were valued at \$15.2 billion in 1988, according to the 1989 U.S. Industrial Outlook, International Trade Administration, U.S. Department of Commerce, p. 28-1 (1989). If the U.S. trade deficit of \$1.9 billion in 1988 (p. 28-2) is added this figure, then the U.S. market can be estimated at \$17.1 billion dollars for 1988. To estimate world shipments from U.S. shipments, a multiplier of about 2.1 to 2.5 is usually about right for high technology electronics fields. If the value of 2.3 is used as a mean, then world shipments, and thus a world market, of \$39 billion for 1988 would be implied.

¹⁷1989 U.S. Industrial Outlook, International Trade Administration, U.S. Department of Commerce, p. 27-2 (1989).

implementing them will gain major competitive advantages in the enormous world market for microwave equipment.

For semiconductor memory circuits, the world market is dominated by Japan. That market amounted to \$11.3 billion per year in 1988¹⁸ for the merchant market alone.¹⁹ Imports of memory circuits are the primary contributors to the U.S. semiconductor trade deficit. That deficit is expected to reach \$1.9 billion in 1989.²⁰ However, a number of U.S. companies are now considering reentering the memory market, or increasing their production if they already in the market.

For optical storage systems, data on U.S. competitiveness over all product lines is lacking. However, in the computer market for optical disk drives used for computers, the U.S. held a 16% market share of the small \$171 million world market in 1987; and that share is expected to increase to 41% by 1991.²¹ In the much larger consumer market for optical disk drives for compact disk players, Japan dominates the market with a 90% share of world production.²² The U.S. is one of the major consumers of these products. In 1988, 5 million units, with an estimated factory-to-dealer sale value of \$1 billion, were sold in the U.S.²³ Further, the world market for all optical disk products, including both read-only and read-write implementations, is expected to grow very rapidly. A ten-fold increase is projected in four years from \$2.0 billion in 1988 to \$21.5 billion in 1992. At that time, optical data storage is expected to account for 25% of the market for all forms of data storage.²⁴

¹⁸Dataquest Industry Service, Executive Issues Volume (November, 1988).

¹⁹The merchant market is distinguished here from the captive market. The merchant market reflects the manufacture of components by companies for sale outside. The captive market reflects the internal market of companies for the components they make for themselves. Market data on the captive market is understandably much more difficult to obtain.

²⁰1989 U.S. Industrial Outlook, International Trade Administration, U.S. Department of Commerce, p. 30-4 (1989).

²¹1988 Disk/Trend Report: Optical Disk Drives, Disk/Trend, Inc., p. SUM-5 (July, 1988).

²²Arnold Mayer and Norbert Schroder, "Opto-Electronic Components and Systems" by Prognos AG of Basel, Switzerland (August, 1988).

²³Data provided by the Electronic Industries Association for total compact disc players which includes "Home CD Players, Audio Systems sold with CD Players, Portable CD Players (Including Combinations), and Autosound CD Players". The dollar figure of \$1 billion is based on an estimate of a \$200 factory-to-dealer price for each unit's CD-player content.

²⁴From synopsis of the study "Office Productivity Impact Using Optical Image Storage and Retrieval" by Electronic Trend Publications (September, 1988). The increase reflects an average compound rate of growth of 81 percent per year for the four-year period. Dataquest projects a similar rate of growth over most of the same period but starts from a smaller estimate of the 1988 level of \$511 million, in "Research Newsletter: Dataquest's Electronics Industry Forecast", p. 6 (May, 1989).

For magnetic storage systems, world shipments of all types of magnetic storage devices have been estimated at \$40 billion in 1987 and can be assumed at least this large for 1988.²⁵ In the computer market for rigid disk drives, the U.S. held a strong 73% share of the world market of \$16.6 billion in 1987 and is expected to remain in a strong position for at least the next several years.²⁶ However, in the computer market for floppy disk drives, the U.S. held only a 5.8% share of the \$2.7 billion world market in 1987 and is expected to continue to lose market share.²⁷ Japan totally dominates the market for video cassette recorders, of which more than \$5 billion were sold in the U.S. in 1988.²⁸

For displays, the U.S. is a manufacturer but not a leader. The 1989 world market for displays is estimated at \$8.88 billion, with \$6.4 billion for cathode ray tube displays and \$1.4 billion for emerging liquid crystal displays. Other display types, in descending order of market share, are vacuum fluorescent, plasma gas discharge, light-emitting diodes (LED), and electroluminescent.²⁹ Vacuum microelectronic displays are still in the research stage.

In the networking area, Japan, Europe, and the U.S. are all very active. Japan is already experimenting with a very high speed version of the Integrated Digital Services Network, operating at 1.2 gigabits per second, about twice the level of the Broadband ISDN system whose protocols will come up for international vote before the CCITT in 1992. In Japan, "ISDN is part of a wide, government-sponsored national technology project" called the Information Network System (INS). It is part of the government's goal to 'take Japan into the "Information Age" as quickly and as coherently as possible.' Similarly, in Europe, most of the ISDN efforts are government controlled. The most advanced is in West Germany, which has been running a pilot fiber optic broadband network, operating at 140 megabits per second, since the mid-1980s. Although trailing Europe, the U.S. will realize Narrowband ISDN services during the early 1990s in one form or another throughout major cities and business centers in the U.S.³⁰

Both Japan and Europe have taken very specific actions that indicate their seriousness about advanced video technology. Japan has already broadcast the Seoul Olympic Games in high

²⁵R.D. Balanson, "Technical Challenges in the Data Storage Industry", a paper presented at NIST Colloquium Series/Interface Science Seminar on Information Storage Technology, June 20, 1989. Corroborated by private correspondence from director of major magnetic research and development center of U.S. university and approximately consistent with estimates such as those appearing in the Electronics January annual world market forecast issues.

²⁶1988 Disk/Trend Report: Rigid Disk Drives, Disk/Trend, Inc., p. SUM-5, (October, 1988).

²⁷1988 Disk/Trend Report: Flexible Disk Drives, Disk/Trend, Inc., p. SUM-5 (November, 1988).

²⁸The U.S. Consumer Electronics Industry: 1989 Annual Review, Consumer Electronics Group, Electronic Industries Association, p. 27 (1989).

²⁹Lawrence E. Tannas, Jr., "Flat-Panel Displays Displace Large, Heavy, Power-Hungry CRTs", IEEE Spectrum, p. 34 (September, 1989). Spencer Chin, "A Varied Brew of Displays", Electronic Products, pp. 19-20 (October, 1989).

³⁰James Martin, "The Development of ISDN Is Proceeding Worldwide", PC Week, p. 68 (April 10, 1989).

definition television to selected public locations. Japan offers a full range of products for high definition television. One example is a magnetic tape recorder that employs eight parallel tracks and very high head speeds (115 miles per hour) to obtain the required record and playback rates.³¹ Japan is also pursuing development of programmatic material and of its domestic market through its Hi-Vision programs. Japan has selected direct broadcast satellites as its initial transmission method for high definition television. Europe plans to broadcast the 1992 Olympic Games in high definition television to selected public locations and has also selected direct broadcast satellites as its initial transmission method.

The U.S. presently has no comparable plans for high definition television broadcasts, but the Federal Communications Commission has granted eight applications for direct broadcast satellites to U.S. companies. One of companies, United States Satellite Broadcasting, plans to launch a satellite built by General Electric Co. in 1992; another company is contemplating a similar launch date.

The emergence of advanced video technology offers the possibility of dramatic changes in competitive positions. As the functions of computers, telecommunication systems, and television begin to merge under the influence of advanced video technology, the world's nations will have opportunities to penetrate new markets for "integrated" products that replace former "single-function" products whose markets they may not have fully penetrated earlier. For example, as computers and television sets merge through advanced video technology, the U.S. will have an opportunity to use its strength in computer technology to penetrate Japanese-dominated television markets. Similarly, Japan will have an opportunity to use its strength in television technology to penetrate U.S.-dominated computer markets.

NIST's Role

NIST can improve the U.S. competitive position by providing U.S. industry with measurement capability required for the development, manufacture, marketplace exchange, and use of advanced video technology. This capability will serve the U.S. well whether it decides to be a producer or just a consumer of advanced video technology.

NIST's high level of measurement capability will be required to address the very difficult measurement problems arising in the several technologies that support advanced video technology.

NIST's impartiality will be essential. NIST is not buyer, seller, or regulator. This impartiality will aid NIST in determining industry's true measurement problems and in achieving adoption of measurement solutions developed by NIST. Further, NIST's impartiality enables NIST's measurement capability to be used in the resolution of key technical issues surrounding advanced video technology. This role will be especially important given the diversity of technical alternatives to be addressed and their national and international dimensions.

³¹Sony High Definition Digital VTR System, Model HDD-1000.

NIST's position as the official source of U.S. measurement capability and national reference standards for measurements will also aid NIST in its role of providing measurement support bearing on representation of U.S. interests in international bodies setting standards affecting the future of advanced video technology.

NIST's continuing close working relationships with U.S. industry and with other Government agencies will enable early identification of key measurement problems and fast adoption of solutions.

NIST's Plan for Measurement Support

U.S. industry's development of advanced video technology will require a major increase in measurement support from NIST. NIST is developing its plans in phases. Phase 1 is the subject of this new program plan. Phase 1 focuses on selected measurement requirements for three of the five supporting technologies: real time signal processing, high data rate transmission, and high density information storage. Later phases of NIST's plans will address additional measurement requirements for these three technologies and the first measurement requirements for the remaining two technologies: vision systems, and displays.

Many of the technologies on which advanced video technology depends -- such as high data rate transmission -- are equally important to other applications. They are already the subject of separate, and coordinated, NIST new program plans. In determining which specific projects NIST will describe in Phase 1 of this new program plan for advanced video technology, versus in other NIST new program plans, NIST has made several distinctions:

If a given type of measurement capability is unique to advanced video technology, then formal, numbered projects aimed at developing that capability are included here.

If a given type of measurement capability is not unique to advanced video technology, but rather is needed broadly, and if it is not already addressed by other NIST new program plans, then formal, numbered projects aimed at developing that capability are included here.

If a given type of measurement capability is not unique to advanced video technology, but rather is needed broadly, and if it is already addressed by other NIST new program plans, then no projects on the same subjects are included here.

Here is a statement of the status of NIST's plans for each of the five supporting technologies, including those for which planning is still underway.

High Resolution Vision

NIST is evaluating the measurement requirements of emerging high resolution vision systems, and will address any key needs uncovered in a later phase of its plans for advanced video technology, as noted above. Possible needs include measurement methods for the accuracy, sensitivity, and resolution of vision systems, particularly when capturing moving images.

Real Time Signal Processing

NIST has identified two classes of measurement support needed for digitally encoded approaches to real time signal processing. Each is described below as a formal, numbered project of this new program plan.

Project 1. Measurements for data compression algorithms: The fundamental impediment to digital video is the incredibly large amount of information required by a fully digitized, moving high resolution video picture: typically 1 gigabit per second. Fortunately, it is possible to develop computer-based data compression algorithms that can reduce the amount of information that must be stored or transmitted to produce a picture with tolerable degradation of quality. A number of organizations are actively developing such data compression techniques. NIST will work closely with them in this development and, based on the knowledge gained, will provide objective techniques for evaluating the efficiency of data compression algorithms. In addition, NIST will provide U.S. industry with convenient access to unclassified image compression technology that has already been developed by the Federal government for its own use.

Project 2. Measurements for data converters: Advanced video technology in digital form will depend critically on the performance of the data converters used for analog-to-digital and digital-to-analog data conversion. To support industrial development of the very high speed data converters required, NIST will develop measurement methods to determine signal degradation during the data conversion process. This project will build on the expertise that NIST has developed in providing calibration techniques for data converters with lower operating speeds than those needed for advanced video technology.

High Data Rate Transmission

For implementation of either direct broadcast satellite transmission or optical fiber cable in service to advanced video technology, measurement support will be needed for determination of component and system performance. Similarly, for implementation of networking capability with either coaxial or optical fiber cable, measurement support will be needed for network protocols. Here are the plans that NIST has defined to address the key measurement needs in these areas.

Measurements for optical fiber transmission components and systems: NIST has defined a separate new program plan, described in Chapter 5, to address the measurement requirements of optical fiber communications systems. Those systems will be needed whatever the future of advanced video technology. Thus no formal project for this area is included in this new program plan for advanced video technology. The plan in Chapter 5 provides for developing measurement support for a broad range of components and technologies, including those critical to advanced video technology. Examples include modulators, multiplexers, optical integrated circuits, amplifier, switches, coherent transmission techniques and devices, and overall system performance measures at the fundamental level, such as signal-to-noise ratio and bandwidth (information handling capacity).

Measurements for microwave transmission components and systems: NIST has also defined a separate new program plan, described in Chapter 8, to address the measurement requirements of high performance microwave systems. Those systems will be needed whatever the future of advanced video technology. Thus no formal project for this area is included in this new program for advanced video technology. The plan in Chapter 8 addresses measurements for high performance components and antennas, including individual components and integrated components and antennas. This new measurement capability will support the special electronic systems and antennas needed for advanced video applications, such as direct broadcast satellites and microwave receivers. It will also support microwave integrated circuits needed for signal processing applications in the preceding category of real time signal processing.

Project 3. Tests for network protocol performance: Higher speed networks, such as Broadband ISDN or Passive Optical Networks, with capability for advanced video technology raise challenging measurement problems. NIST's contribution will be to develop the tests required to assess the technical performance of alternative network strategies, with a special focus on the problems associated with the very high information capacity required for advanced video technology. These tests are required for developing, marketing, and using network hardware and software. NIST's work will be conducted in close collaboration with U.S. vendors and users of network equipment, and with international counterparts in standards formulation.

This project will complement work in a related but separate NIST new program plan that focuses on conformance tests and implementation agreements for both Narrowband ISDN and Broadband ISDN. That plan is not included as a chapter in this document. Conformance tests are required to establish the compatibility of vendor equipment with protocol standards developed by international standards bodies. Implementation agreements are agreements among vendors and software developers that resolve options or other ambiguities within the international protocol standards. Both conformance tests and implementation standards therefore complement the protocol standards. They are essential in enabling realization of commercial systems by industry. NIST provides technical information that the State Department relies upon in its capacity as the official U.S. representative to the international body, CCITT, that adopts standard conformance tests.

NIST collaborates with the National Telecommunications and Information Administration of the Department of Commerce on networking matters. The NTIA, along with industrial bodies, especially the American National Standards Institute, provides critical information needed by the State Department as the official U.S. representative to the international standards bodies that establish the protocol standards themselves.

High Density Information Storage

NIST has evaluated the measurement requirements of high density magnetic information storage. The requirements are described as part of a separate new program of measurement support for magnetic systems broadly in Chapter 4. That program will address development of measurement methods for fundamental magnetic properties, such as coercivity,

magnetization properties, and demagnetization properties, critical to all magnetic recording processes, including those for advanced video technology. However, to support industrial pursuit of the ultimate information densities, which would greatly benefit advanced video technology, NIST will carry out the project below as part of this new program plan:

Project 4. Measurements for magnetic high density information storage: NIST will develop measurements for magnetic properties of magnetic media with high information density. For example, NIST will develop measurement methods with extraordinarily high geometric resolutions, including those approaching the atomic level.

High Resolution Displays

NIST will investigate the measurement requirements of emerging display technologies. This investigation will be a complex one, since a broad range of display technologies are under consideration by industry. In fact, some are still in the earliest stages of research. Any critical measurement requirements uncovered will be addressed in later phases of this new program.

A key source of information about the future of alternative display technologies will be the new program of the Department of Defense (DARPA). DARPA funded a research and development program in 1989 at a level of \$30 million per year over three years to improve domestic display technology. This program will aid in identifying appropriate technologies for different applications of advanced video technology. The program will also surface critical measurement problems that NIST must address.

Development of an Advanced Video Technology Test Facility

NIST feels that the development of advanced video technology, and the careful consideration of the alternatives that it presents, will require the creation of a special test facility at NIST.

Project 5. Development of advanced video test facility: NIST will develop a laboratory facility that will permit the evaluation of key elements of advanced video technology including recording, data compression, data transmission, reception in a range of formats, display of pictures, and reproduction of sound. This facility will employ the best current measurement methods and will serve as a testbed for new measurement methods developed by this new program. It will also serve in identifying needed new measurement capability. This facility will be analogous to NIST's existing Automated Manufacturing Research Facility in the following ways:

1. The facility will be staffed by guest workers from industry and universities as well as NIST staff so that there can be rapid transfer of NIST advances to the private sector.
2. The research and development results are intended to be generic and widely distributed.

3. The facility will be an open facility, so that innovative small companies can test new concepts without the requirement for major, highly speculative investment in laboratory facilities. After they have convinced themselves of concept validity, however, they would be expected to invest in their own facilities to develop and test proprietary products.

The facility will be important as a counterbalance to other international testing facilities. For example, the Soviet Union has offered to provide a neutral international test bed for HDTV. This invitation will probably be accepted by foreign manufacturers and by some domestic manufacturers. The NIST staff will monitor the capability and performance of this test facility and attempt to provide the domestic industry with comparable or better test capability in the U.S.

NIST staff will use the test facility to work with industry groups and regulators to help assure that the test results on which they rely are a valid basis for decision making. NIST will collaborate closely with the private sector groups already formed and with any further groups formed, to test the feasibility of proposed standards. The Advanced Television Testing Center, for example, was established by television broadcasters to test a scheme to use a combination of two existing channels to broadcast HDTV. That association anticipates that its results will contribute to the decision making process within the Federal Communications Commission (FCC).

Chapter 10
CHALLENGES TO EMERGING TECHNOLOGIES:
ELECTROMAGNETIC COMPATIBILITY
New Program Plan

Summary

We live in a world that increasingly depends on electronic systems in virtually every arena of life to provide functions without which our society could not continue or perhaps even survive, at least without wrenching change. Yet continued successful operation of these systems faces a challenge that is now only beginning to be understood and addressed in all its ramifications. That challenge is the ever-growing presence of unwanted electromagnetic energy -- electromagnetic interference (EMI) -- that threatens the proper operation of electronic systems. Society's response must be to take those steps that ensure an acceptable degree of electromagnetic compatibility between systems and the environments in which they operate. As used here, electromagnetic compatibility (EMC) refers to the degree with which electronic and electrical components, devices, and systems can function without interfering with each other's intended operation and can function in the electromagnetic environments in which they are intended to be used. As more and more sources of electromagnetic energy are added to the environment, it becomes increasingly important to know the state of electromagnetic compatibility among the components of a larger entity, for example, among the electronic systems of a modern airliner, automated factory, or community. Proliferation of modern electronic devices and systems has led to increasing susceptibility to interference from other electrical signals.

The urgency and importance of the EMI challenge has led NIST to plan a comprehensive measurements program to provide the support industry and others need to meet it. This chapter presents the proposed NIST response. It opens with a discussion of the market impact of EMC/EMI issues, then illustrates the pervasive aspect of EMC/EMI problems with a number of anecdotal accounts. A brief statement of the importance of measurements to the resolution of EMC/EMI issues and the significant role that NIST can play is followed by details of the planned NIST technical response. Notes at the end of the chapter (identified by bracketed numbers) provide additional information on topics that may not be familiar to the non-technical reader.

Markets

Modern society depends so much on electronic systems where its members live and work and play and in the transport systems without which they would not survive that the impact of EMC/EMI issues is hard to assess in terms of hard dollars. The electronics industry, with annual domestic sales in excess of \$248 billion per year (1988) is critically concerned with electromagnetic compatibility (EMC) for almost any application involving electronics one can think of. The adverse effects of EMI can range in importance from hash on your television screen to automobiles that don't start, to the loss and degradation of vital data, voice, and video information in telecommunication systems, to aircraft that crash when their controls fail to respond to their pilots' commands. EMC/EMI issues are of vital concern to specific U.S. markets, including the computer market (\$51 billion sold domestically in 1988), the radio communication and detection market (U.S. companies shipped about \$54 billion in 1988), and

the electronic components market (U.S. companies shipped \$57 billion in 1988). EMC/EMI issues have the potential to impact the estimated 2.6 million jobs in the United States that depend on electronic markets but also many more in those industries that depend on reliable operation of electronic equipment.

Measurements are key to resolving EMC issues and are vital to marketplace interactions, especially as worldwide concern for EMC grows. For example, some years ago, a \$400 million market for electronic measuring instruments was closed to U.S. companies until adequate EMC/EMI test methods were developed to convince the Europeans that their specifications were being met. In another example, the sudden imposition by the Canadian government of regulated electromagnetic emission levels caused concern in the U.S. automobile industry and led its members to establish EMC/EMI measurement facilities so that they could demonstrate compliance and retain their Canadian markets. In both of these examples, NIST was called upon to provide measurement assistance.

Electromagnetic Interference

In the modern world, unwanted electromagnetic energy can be found over a very wide range of frequencies, for example, from the 60 Hz of the U.S. power grid to 110 GHz and beyond. Most practical EMC/EMI issues relate to the performance of equipment that is electronic in nature or that depends on electronic circuits for its operation, especially in the fields of radio and television broadcasting, other terrestrial and satellite communications, navigation, and radar. Interference between units takes the form of inadvertent coupling of radiated or guided electromagnetic energy between them. Unintentional paths for electromagnetic energy may be any form of electrical conductor, including power cords. Both types of unwanted electromagnetic energy are referred to as electromagnetic interference (EMI). From the standpoint of a victim system, EMI is noise.

There are many situations in which complex electronic systems are expected to work together and in the presence of externally produced EMI. Although it may be possible to monitor how well a very simple system functions as all its components are exercised in all possible combinations of modes of operation and for each combination of modes in all the electromagnetic environments to which the system will be exposed, in general this type of test is not practicable. Even if this type of operational evaluation is feasible in a very special case, a subsequent change in one component may invalidate the results.

A rational approach to achieving EMC is to evaluate the emissions from each component separately and to compare these results to some previously determined specification. For example, the Federal Communications Commission (FCC) specifies the allowable amounts of electromagnetic energy that can be emitted by "computing devices." To be able to make an evaluation of how much and what kind of electromagnetic energy is being emitted by a system requires the capability to make accurate measurements of the quantities discussed above, in accordance with the applicable specification. Measurements thus lie at the heart of resolving EMC/EMI issues. The National Institute of Standards and Technology (NIST), charged with providing reference measurements traceable to national standards, can provide the basis needed for these measurements.

In a few cases, adequate measurement technology is available to resolve EMC/EMI issues. However, specifications for the performance of advanced electronic systems already have been put into place requiring measurements that are not yet available. In other cases, measurements have not been developed to support the latest systems operating at higher levels of performance than heretofore. The lack of adequate measurement support to resolve EMC/EMI problems in advanced systems will hinder their introduction and may result in new tragedies if introduction is attempted without adequate EMC/EMI evaluation. Yet society needs the new capabilities that advanced systems offer now.

Proposed NIST Response

The NIST response focuses on the most demanding needs of industry and the EMC/EMI testing community. In general, NIST will develop standardized test methods, calibration and other measurement services, and transfer standards. NIST has assigned its highest priority to the area of standard electromagnetic field generation in support of EMC/EMI measurements in order to be able to provide appropriate measurement services over the range of commercially most significant frequencies (topics: anechoic chamber, TEM cell, ground-screen range, near-field arrays, measurement services). A second area of concentration will be on electromagnetic field sensors that can be used as transfer standards and for implementing emission and immunity measurements (topics: electrical and thermal sensors, electro-optic sensors, electromagnetic energy density sensors). Regulations tend to specify the amount of electromagnetic energy a given device or system is allowed to emit; test methodology in support of emissions measurement is the third NIST area (topics: TEM cell, reverberation chamber, standard electric field emitter). Immunity issues are vital to those who have to make electronic systems work together and in real-world environments; test methodology in support of immunity measurements is the fourth NIST area (topics: time-domain range, time-domain antennas, time-domain methods for whole system testing, TEM cell, reverberation chamber, conducted EMI, shielding effectiveness of materials, shielding effectiveness of cables, connectors, and housings). NIST needs to be able to respond to various requirements of industry and the EMC/EMI testing community that cannot be classified as falling under any of the these four major thrusts. The topics are harmonization of standards, measurement of electromagnetic fields radiated by electrostatic discharge, characterization of electromagnetic environments, and electromagnetic evaluation of electroexplosive devices.

Introduction

We live in a world that increasingly depends on electronic systems in virtually every arena of life to provide functions without which our society could not continue or perhaps even survive, at least without wrenching change. Yet continued successful operation of these systems faces a challenge that is now only beginning to be understood and addressed in all its ramifications. That challenge is the ever-growing presence of unwanted electromagnetic energy -- electromagnetic interference (EMI) -- that threatens the proper operation of electronic systems. Society's response must be to take those steps that ensure an acceptable degree of electromagnetic compatibility between systems and the environments in which they operate. As used here, electromagnetic compatibility (EMC) refers to the degree with which electronic and electrical components, devices, and systems can function without interfering with each

other's intended operation and can function in the electromagnetic environments in which they are intended to be used. As more and more sources of electromagnetic energy are added to the environment, it becomes increasingly important to know the state of electromagnetic compatibility among the components of a larger entity, for example, among the electronic systems of a modern airliner, automated factory, or community. Proliferation of modern electronic devices and systems has led to increasing susceptibility to interference from other electrical signals.

The urgency and importance of the EMI challenge has led NIST to plan a comprehensive measurements program to provide the support industry and others need to meet it. This chapter presents the proposed NIST response. It opens with a discussion of the market impact of EMC/EMI issues, then illustrates the pervasive aspect of EMC/EMI problems with a number of anecdotal accounts. A brief statement of the importance of measurements to the resolution of EMC/EMI issues and the significant role that NIST can play is followed by details of the planned NIST technical response. Notes at the end of the chapter (identified by bracketed numbers) provide additional information on topics that may not be familiar to the non-technical reader.

Markets

Modern society depends so much on electronic systems where its members live and work and play and in the transport systems without which they would not survive that the impact of EMC/EMI issues is hard to assess in terms of hard dollars. The electronics industry, with annual domestic sales in excess of \$248 billion per year (1988)¹ is critically concerned with electromagnetic compatibility (EMC) for almost any application involving electronics one can think of. EMC/EMI issues are of vital concern to specific U.S. markets, including the computer market (\$51 billion sold domestically in 1988), the radio communication and detection market (U.S. companies shipped about \$54 billion in 1988), and the electronic components market (U.S. companies shipped \$57 billion in 1988).² EMC/EMI issues have the potential to impact the estimated 2.6 million jobs in the United States that depend on electronic markets but also many more in those industries that depend on reliable operation of electronic equipment.³

As will be shown, measurements are key to resolving EMC issues and are vital to marketplace interactions, especially as worldwide concern for EMC grows. For example, some years ago, a \$400 million market for electronic measuring instruments was closed to U.S. companies until adequate EMC/EMI test methods were developed to convince the Europeans that their specifications were being met. In another example, the sudden imposition by the Canadian

¹1989 Electronic Market Data Book, EIA Marketing Services Department, Electronic Industries Association, p. 3 (Washington, DC 1989).

²1989 U.S. Industrial Outlook, International Trade Administration, U.S. Department of Commerce, pp. 26-1, 27-1, 30-1 (January, 1989).

³"A Strategic Industry at Risk: A Report to the President and The Congress from the National Advisory Committee on Semiconductors", Advance Edition, p. 5 (Washington, DC, November, 1989).

government of regulated electromagnetic emission levels caused concern in the U.S. automobile industry and led its members to establish EMC/EMI measurement facilities so that they could demonstrate compliance and retain their Canadian markets. In both of these example, NIST was called upon to provide measurement assistance.

Electromagnetic Interference

In the modern world, unwanted electromagnetic energy can be found over a very wide range of frequencies,^[1] for example, from the 60 Hz of the U.S. power grid to 110 GHz and beyond. The domain of interest for electromagnetic compatibility concerns is shown in Table 1.

Most practical EMC/EMI issues relate to the performance of equipment that is electronic in nature or that depends on electronic circuits for its operation, especially in the fields of radio and television broadcasting, other terrestrial and satellite communications, navigation, and radar. Interference between units takes the form of inadvertent coupling of radiated or guided electromagnetic energy between them. Unintentional paths for electromagnetic energy may be any form of electrical conductor, including power cords. Both types of unwanted electromagnetic energy are referred to as electromagnetic interference (EMI). From the standpoint of a victim system, EMI is noise.

Table 1
Overview of Frequency Spectrum

Hertz (Hz)	= 1 Hz	ultra low frequency waves extreme low frequency waves	60 Hz power	
Kilohertz (kHz)	= 10 ³ Hz	extreme low frequency waves very low frequency waves low frequency waves		
Megahertz (MHz)	= 10 ⁶ Hz	medium frequency waves very high frequency waves ultra high frequency waves	AM radio FM radio, TV, etc. TV, other	
Gigahertz (GHz)	= 10 ⁹ Hz	centimeter waves millimeter waves sub-millimeter waves	microwaves	
Terahertz (THz)	= 10 ¹² Hz	far infrared light near infrared light visible light	light	
Petahertz (PHz)	= 10 ¹⁵ Hz	ultraviolet light x-rays		

Practical Examples of EMC/EMI Challenges

There are many situations in which complex electronic systems are expected to work together and in the presence of externally produced EMI.

A modern office building is full of electronically controlled heating, ventilating, and air-conditioning systems; communications systems, such as telephone, computer networks, and facsimile transmission; and computers. Activation of a telephone should not change the calculation in a computer spreadsheet.

Consider an airliner having electronic flight and engine controls, autopilot, digital cockpit displays, communications systems, transponder, navigation systems, weather and anti-collision radar, microwave ovens, entertainment systems, and even radio receivers, tape players, and computers brought on board by passengers. All these systems generate electromagnetic fields and are potential sources of EMI as well as potential victims. They must operate together, without any component interfering to any significant degree with any other component. Both emissions and susceptibility issues are involved.

The aircraft case also dramatizes the issue of susceptibility: not only must the individual electronic subsystems and systems work in electromagnetic harmony, but the aircraft as a whole has to operate in electromagnetic harmony with its flight environment, including the electromagnetic environment produced by broadcasting; commercial communications; and traffic control, weather, and defense radars.

Unfortunately, this was not true of one type of Army helicopter, several of which crashed - - killing a number of men -- because of interference with flight-control systems by commercial broadcasts. Airliners in revenue service have also experienced uncommanded changes in altitude greater than one flight level to the next that are believed to have resulted from electromagnetic interference with the autopilots. Since altitude separation is a fundamental principle of air traffic control, the resulting potential for collision threatens the lives of all aboard.

Other examples:

- o Hash on the home television screen.
- o Electronically controlled automobiles don't start.
- o Vital data, voice, or video information is lost or degraded in telecommunication systems.
- o Communications with Air Force One (with the President aboard) caused garage-door openers to activate as the aircraft flew overhead. Any effect of garage-door control transmitters on the aircraft's communications has not been reported.

- o In at least one instance, the inadvertent signals produced by relays in home appliances caused the electronic furnace control to demand full heat; a secondary failure in furnace operation burned down the house.
- o Signals associated with on-the-spot television coverage of a Space Shuttle landing interfered with communications systems on the vehicle. The Shuttle gets only one chance to land.
- o Patients with early-model heart pacemakers experienced traumatic disruption of the pacemaker's operation when they heated sandwiches from vending machines in the machines' accompanying microwave ovens.
- o The driver of at least one eighteen-wheel tractor-trailer rig is known to have lost control when the trailer's electronically controlled brakes were prevented from operating as a result of Citizens' Band radio operation in one or more near-by vehicles.
- o A British warship must turn off its protective radar in order to send a signal to the Admiralty. As a result an undetected incoming Exocet missile destroys the ship.

New concerns have arisen for the safety and well-being of organisms (including man) in electric and magnetic fields.⁴ Test methods and associated instrumentation developed for EMC/EMI issues can provide a well-grounded basis for measurements of fields in biological exposure experiments.

Importance of Measurements in EMC/EMI Evaluation

Although it may be possible to monitor how well a very simple system functions as all its components are exercised in all possible combinations of modes of operation and for each combination of modes in all the electromagnetic environments to which the system will be exposed, in general this type of test is not practicable. Even if this type of operational evaluation is feasible in a very special case, a subsequent change in one component may invalidate the results.

A rational approach to achieving EMC is to evaluate the emissions from each component separately and to compare these results to some previously determined specification. For example, the Federal Communications Commission (FCC) specifies the allowable amounts of electromagnetic energy that can be emitted by "computing devices." To be able to make an evaluation of how much and what kind of electromagnetic energy is being emitted by a system requires the capability to make accurate measurements of the quantities discussed above, in accordance with the applicable specification. In another example, the Center for Devices and Radiological Health of the Food and Drug Administration sets the allowable limits for the amount of electromagnetic energy that leaks from microwave ovens. Again, accurate measurements of the resulting fields are required to demonstrate compliance.

⁴A recent example receiving wide circulation: Paul Brodeur, "Family Circle Radiation Alert: Powerlines and Appliances -- Are You at Risk?", Family Circle, p. 85 and following (November 7, 1989).

Measurements thus lie at the heart of resolving EMC/EMI issues. The National Institute of Standards and Technology (NIST), charged with providing reference measurements traceable to national standards, can provide the basis needed for these measurements.

Need for Advanced EMC/EMI Measurement Capabilities

In a few cases, adequate measurement technology is available to resolve EMC/EMI issues. However, specifications for the performance of advanced electronic systems already have been put into place requiring measurements that are not yet available. In other cases, measurements have not been developed to support the latest systems operating at higher levels of performance (e.g., for microwave systems, providing greater frequency coverage, more sensitivity, and greater dynamic range) than heretofore. The lack of adequate measurement support to resolve EMC/EMI problems in advanced systems will hinder their introduction and may result in new tragedies if introduction is attempted without adequate EMC/EMI evaluation.

Society needs the new capabilities that advanced systems offer now. For example, the shorter the wavelength, the greater the spatial discrimination of a radar. Proposed vehicular proximity-sensing systems need this improved performance in order to save many lives yearly. Traffic control radar is already hard-pressed to meet safety requirements, and additional thousands of new aircraft have been ordered through the end of the century. To avoid Tenerife-type accidents, a controller must be able to identify aircraft unambiguously so that he or she may issue instructions directed to the pilots of the correct aircraft. Military systems need better imaging capability in order to map terrain and to identify targets.

The capabilities provided by state-of-the-art and developing semiconductor devices are needed now in many fields; marketplace demands drive the continuing advances. Yet these devices and the systems they make possible tend to become ever more susceptible to EMI as the devices themselves and their individual elements grow smaller. Because the signal levels of these devices tends to be lower, their vulnerability to electromagnetically induced upsets increases. Reduced power requirements render them more sensitive to fluctuations in the power supplied them. Operation at higher frequencies implies that more conducting structures will serve as inadvertent transmitting and receiving antennas, as the corresponding wavelengths become comparable to instrument and component dimensions.

Measurement Issues

A principal barrier to achieving electromagnetic compatibility lies in the measurements needed to support and verify it. Consider a personal computer. Federal regulations stipulate maximum levels of electromagnetic energy that the computer can transmit in specified frequency bands and the measurement methods that are to be used to establish the actual levels for a given unit. Acceptable measurements must be traceable to national standards. How can one determine that a given computer satisfies the specifications?

An obvious requirement is for a reliable, accurate tool for measuring electromagnetic fields over the appropriate frequency ranges. Such tools are small receiving antennas also called field sensors or field probes. In this example, field sensors would be used to determine

emissions from the computer and also that the measurement site was acceptably free from EMI in the frequency range of interest. If the measurements are to be traceable to national standards, the antenna or sensor must be calibrated, that is, its performance must be determined empirically by comparison with a reference sensor.

Reference sensors used in this way are known as transfer standards because they transfer the accuracy of measurement at a higher (more accurate) level in the measurement chain to a working (less accurate) level. The transfer-standard sensor in turn must be calibrated by comparison with a still more accurate reference sensor at a still more accurate level or by direct calibration measurements at NIST. Ultimately, NIST needs to provide means for empirical measurement of transfer-standard antennas and sensors supporting measurements to determine compliance with regulations. As part of its response to this need, NIST proposes to continue the development of a number of special facilities for generating reference electromagnetic fields into which an antenna or sensor may be positioned to determine its performance.

Different facilities offer different ranges and accuracies. One possibility is characterization of the customer's sensor on a ground-screen range,^[2] as this type of facility is likely to be used by the customer for compliance measurements. The comparison instrument would be an NIST transfer-standard sensor.

NIST also must calibrate the transfer-standard sensor. One choice of a calibration facility is a microwave anechoic chamber^[3]. Several different methods are available for measuring sensor performance. For example in one method, the sensor is mounted in the anechoic chamber and the energy from a special transmitting horn is directed onto it. The horn is known as a standard gain horn; the electromagnetic field at a given distance from the horn can be calculated when the power supplied to the horn is known and controlled through measurement. The determination of power supplied to the horn is traceable to national electrical standards. This arrangement permits accurate determination of the response of the sensor to given fields. It should be noted that both the sensor and the associated instrumentation that transforms the signal from the sensor into a dial or other readout display need to be calibrated. The current NIST anechoic chamber has been characterized for the range 200 MHz to 18 GHz.

Another calibration facility that could be used is a transverse electromagnetic (TEM) cell^[4]. TEM refers to the nature of the plane-wave fields that are produced within the cell. The sensor is placed in one of the two cavities of the cell where its response to given fields may be measured. The determination of the field is traceable to national electrical standards.

The computer example discussed above demonstrates the need for NIST to be able to generate standard electromagnetic fields for the calibration and verification of performance of sensors and EMI antennas. It hints at the need for the development of sensors and methodology for transferring the results of reference measurements from one calibration laboratory (especially NIST) to another; sensors and associated methodology are also needed for survey purposes and for other reference measurements. In the example part of the test methodology is provided by the appropriate regulations. NIST has provided technical input to the development of regulations; industry has asked NIST to develop instrumentation and

associated methodology for assessing the immunity of devices and systems with respect to EMI^[5]. Likewise, NIST has been asked to develop methods and means for measuring the emissions from devices and systems.

Proposed NIST Response

NIST proposes responses in all of these areas. In general, NIST will develop standardized test methods, calibration and other measurement services, and transfer standards in response to needs. In the following sections, NIST's technical plans are identified under headings that correspond to five projects: (1) standard electromagnetic field generation in support of EMC/EMI measurements (anechoic chamber, TEM cell, ground-screen range, near-field arrays, measurement services); (2) sensor technology (electrical and thermal sensors, electro-optic sensors, electromagnetic energy density sensors); (3) device/system emissions (TEM cell, reverberation chamber, standard electric field emitter); (4) device/system immunity (time-domain range, time-domain antennas, time-domain methods for whole system testing, TEM cell, reverberation chamber, conducted EMI shielding effectiveness of materials, shielding effectiveness of cables, connectors, and housings); and (5) special topics (harmonization of standards, measurement of electromagnetic fields radiated by electrostatic discharges, electromagnetic environment, electroexplosive devices). The order of the five projects indicates the nominal order of implementation.

Project 1: Standard Electromagnetic Field Generation in Support of EMC/EMI Measurements

Standard electromagnetic fields are used for calibration of antennas, hazard meters, and transfer standards; for antenna and probe research and development; and for EMI susceptibility testing. There are various ways of establishing standard fields, each with its own characteristics. Factors associated with the different methods are frequency range, size of test volume, isolation from outside interference, maximum field intensity, achievable accuracy, etc. Three principal field-generation facilities that NIST will use are microwave anechoic chambers, transverse electromagnetic (TEM) cells, and the ground-screen range. In addition, NIST plans to develop a near-field phased-array facility. These four activities are treated below. The last section describes proposed measurement services, which constitute one of the major uses of the field-generation facilities.

Anechoic Chamber

In general, NIST will develop methods and techniques for establishing reference electromagnetic (EM) fields in an environment approximating that of free space and for evaluating and calibrating antennas and sensors in such an environment, with continuous-wave, pulsed, and non-sinusoidal fields.

New chamber -- To meet lower-frequency needs for which industry is calling for help urgently, NIST proposes to construct a new, larger chamber in order to make anechoic measurements and calibrations available over the commercially vital range of 30 MHz to about 2 GHz. NIST has identified this facility as its most urgent EMC/EMI need. While TEM cells provide coverage of lower frequencies, they can accommodate only relatively small

probes, not the full-size antennas for which calibration is being requested. Furthermore, there is an uncovered gap between the TEM cells upper practical limit of about 150 MHz and the lower limit of the existing anechoic chamber of about 200 MHz (which cannot be extended because of physical size).

Existing chamber -- To meet existing requirements, NIST will characterize this anechoic chamber for the range 200 MHz to 40 GHz, the upper limit responding to communications industry needs. NIST will then develop field-generation capability in small (2-GHz) frequency bands centered at 60 GHz and at 95 GHz to meet needs identified for supporting new systems that are now under development in these bands. When a new chamber is constructed, NIST will convert the existing chamber to a microwave/millimeter-wave facility covering the range 1 to 110 GHz.

The need for higher frequencies is driven by increased activity at millimeter-wave frequencies. Specifically, the need for antenna and hazard-meter calibration above 40 GHz will increase as these frequencies are used more in satellite communications. Industry projects already require calibration capabilities up to about 110 GHz.

TEM Cell

NIST will develop new measuring techniques to support industry needs for the calibration of transfer-standard sensors and hazard meters and to support in-house sensor development.

Ground-Screen Range

In general, NIST will develop methods and techniques of establishing continuous-wave reference electromagnetic fields on a ground screen and develop and improve calibration methodology for antennas over a ground screen. NIST plans to address difficulties encountered in its use of the present ground-screen range to establish a horizontally-polarized electric field in the frequency range 30-1000 MHz for use in antenna factor calibrations, needed by industry. In particular, NIST will address the presence of unacceptably high ambient fields at lower frequencies by investigating an improved ambient-subtraction method and methods of using an automatic network analyzer for a three-antenna measurement of antenna factor (a measure of antenna performance).

NIST will also develop improved standard dipoles and procedures to determine the magnitude of the field established. NIST will compare the results of measurements with these dipoles with other reference fields, such as that generated in the NIST anechoic chamber. NIST then plans to distribute specimen dipoles to other calibration laboratories for intercomparison to improve the basis for measurement agreement among their constituencies.

NIST further will implement methodology for a check standard, develop improved measurement methods for log-periodic and other large or axially asymmetric antennas, and develop a firm foundation for vertical antenna factor measurements. Vertical-polarization antenna factor measurements are needed for certain FCC compliance tests.

Near-Field Arrays

NIST will develop near-field arrays (assemblies consisting of many antenna elements in a defined pattern) having wider bandwidth than the present seven-element array used to validate the basic concept and associated methods for evaluating and calibrating antennas and for performing EM susceptibility tests. In particular, NIST plans to use broadband elements and frequency-dependent element excitation to achieve a range of operation of about 50 MHz to 1 GHz. Some of the new EM susceptibility standards require very high field strengths which cannot be achieved in the far field of a single antenna. There is an emerging interest in the use of near-field arrays in U.S. industry and government, and other countries are also pursuing their use, with marketplace implications. Near-field arrays have the capability of producing strong, uniform fields within a volume located close to the array. Thus they can be used whether in an anechoic chamber or over an outdoor ground screen.

Measurement Services

NIST plans to extend the range of anechoic chamber services to 40 GHz -- probably in two stages, with a first extension to 26 GHz. NIST also plans to begin offering regular measurements of the vertical-polarization antenna factor on the ground screen when the needed theoretical basis has been established. The most common applications of these calibrations will be for hazard meters, FCC compliance testing, foreign regulatory agency compliance testing, and research and development in various areas of electromagnetics.

Project 2: Sensor Technology

Work on development of transfer-standard sensors or probes is loosely divided into three areas, sensors that depend on electrical or thermal detection principles, sensors that depend on electro-optical (EO) detection principles, and sensors that respond to energy density. The first category comprises new thermo-optic designs currently under development as well as conventional antenna/detector (dipole/diode) designs. These designs typically measure only the magnitude of the field, with no frequency or phase information. The second area consists of EO sensors, which can preserve the full phase and frequency information of the signal. In both cases, the emphasis is on measurement of electric rather than magnetic fields.

Electrical or Thermal Sensors

To respond to needs driven by increasing use of the upper microwave and millimeter-wave frequencies in civilian communications, military communications, and remote sensing, NIST will extend the 18-GHz upper limit of the present resistively tapered dipole sensor used as a transfer standard. In the first step, NIST will use 6-mm dipoles to cover the range 18 to 26 GHz. A second step will extend the range to 40 GHz. For frequencies above 40 GHz, NIST will pursue the development of thermo-optic designs based on using a fluoroptic thermometer to sense the temperature rise of a resistive structure when it is exposed to an electric field. In this work, NIST will study the effects of different configurations of the resistive structure on sensitivity.

Electro-Optical Sensors

As systems which operate at the higher microwave and millimeter-wave frequencies become more common, industry and others are expected to seek NIST support for the characterization of their emissions and susceptibility to EMI. In response, NIST will develop advanced photonic sensors^[6] as measurement standards for characterizing the required test fields, including high-strength impulsive fields. Specifically, NIST will develop an isotropic-response sensor using an integrated optics modulator that has a frequency response to above 3 GHz. NIST will study the use of Pockels cell and other electro-optic modulators for characterizing electromagnetic pulses with high field strengths in the range 1 volt per meter to 100 kilovolts per meter. NIST will continue to investigate various photonic principles for use at higher frequencies, with particular attention to designing for high sensitivity.

Electromagnetic Energy Density Sensors

Sensors for survey use of electric fields present at a given site, such as in a building or in a school playground, are commercially available, patterned on NIST developments. However, electromagnetic energy density, not just electric field value, is frequently the quantity that is most significant in determining the effect of interfering fields on electronic systems or biological organisms. The electric field value may be converted to energy density through a simple formula only in the special case that the sources of the field are far away, several kilometers for the antennas and frequencies used in television broadcasting, for example. However, in most real-world situations, there are conductive structures such as pipes, girders, metal fences, metal furniture, etc. that can reflect electromagnetic energy and thus act as secondary radiators. The presence of these secondary radiators close to the point at which the field is measured invalidates a simple conversion to energy density. NIST will respond to this need by developing sensors that respond to the components of both electric and magnetic fields simultaneously, from which energy density can be calculated.

Project 3: Device/System Emissions

There is a need for theoretically based, reliable, well-characterized test methods for the assessment of the electromagnetic emissions from devices and systems. In response, NIST will pursue further development and modification of the TEM cell, new applications of the reverberation chamber, extension of the time-domain range, development of new broadband phase-linear antennas (also referred to as time-domain antennas), and the design and fabrication of a control-standard radiator. Note: The TEM cell and reverberation chamber are used for both emission and immunity assessments.

TEM Cell

To provide emissions characterization for larger objects at higher frequencies than the simple TEM cell can support, NIST will study two extensions of TEM cell technology intended to increase the maximum frequency attainable. NIST will investigate the theory, design, and operation of a hybrid TEM cell/reverberation chamber. NIST will also investigate horn-driven chambers. In this concept, NIST would use a ridged horn as one end of the chamber; the opposite end would be loaded with absorber. The fundamental mode would be a

transverse electric (TE) mode rather than the TEM mode, since there would be no central septum. Although the TE mode does not simulate a free-space plane wave, it does provide a well-characterized electromagnetic field for measuring emissions (or immunity). NIST plans to use horn-driven chambers in the range 20 MHz to 1 GHz to overlap the frequency coverage of TEM cells and reverberation chambers (which have a lower practical limit of about 500 MHz), thus filling a gap in coverage and meeting needs that are not at present satisfied.

Reverberation Chamber

In response to requests from the EMC/EMI testing community, NIST will provide a better understanding of the application of reverberation chambers^[7] as an emissions (and immunity) evaluation tool by developing underlying theory.

Standard Electric-Field Emitter

NIST will provide technical support, develop artifact devices, and furnish calibration for the national Voluntary Laboratory Accreditation Program (NVLAP) for accreditation of public and private laboratories relating to EMC/EMI measurements. NIST will subsequently evaluate and provide industry with needed improved techniques for acceptance testing, especially in the areas of radiated emissions and radiated and conducted susceptibility, including methods that address the requirements of contractors who must comply with MIL-STD-462 requirements. For conducted emissions, NIST plans to develop standard devices (such as a switching power supply that is rich in emissions) to support NVLAP testing over the frequency range 0.45 to 30 MHz. For radiated emissions, NIST will continue the development and evaluation of comb-generator radiating monopoles for use as artifact devices for compliance testing of electronic devices (e.g., FCC testing of Type B devices for radiated limits) and for MIL-STD-462 testing for limits of radiated emissions. NIST will also pursue the development of two types of sine-wave reference standard radiators for use as transfer standards in testing that requires controlling the radiofrequency output level to a predetermined value, in order to produce a given field strength (either vertically or horizontally polarized) at a given position. NIST will use fiber-optic links to control radiated frequency and amplitude. NIST will calibrate instrumentation for measuring and verifying the field strength produced by the standard emitter at the ground-screen range over the frequency range 10 to 1000 MHz.

Project 4: Device/System Immunity

NIST will pursue a number of projects for developing new methodology and new test procedures for the measurement of electromagnetic immunity. Because the field of EMI/EMC is relatively young, it does not have an extensive system of standards, and many of the standards which do exist lack a solid metrological foundation. In response, NIST will promote new standards for the immunity properties of electrical and electronic equipment and develop a better theoretical basis for existing standards. NIST will also respond to needs for new measurement methods that are quick and efficient as well as theoretically sound. NIST plans to develop test methods and physical standards in the following areas: time-domain techniques for evaluating the response of a system to a broad spectrum of frequencies simultaneously, thus providing a simulation of electromagnetically complex real-world

environments; conducted EMI; shielding effectiveness (SE) of materials; SE of cables, connectors, and containers; voluntary and government standards; electrostatic discharge; electro-explosive devices; time-domain methods for whole system testing; and the EM environment.

Time-Domain Range

NIST will develop methods and techniques for establishing radiated pulses and to further develop time-domain measurement techniques in support of the design and development of phase-linear antennas. NIST plans to extend the capabilities of its existing time-domain range from an upper limit of about 12 GHz to above 20 GHz. NIST will investigate the advantages of "synthetic" time-domain techniques, that is of procedures that involve collecting data in the frequency domain and then transforming the data into the time domain. NIST will also pursue improving the signal-to-noise ratio of the system by storing several kilovolts on the cone and then initiating a discharge with a laser-activated switch. NIST expects a side benefit to be a significant reduction of the rise time of the pulse, to on the order of 5 ps. NIST will further upgrade its existing time-domain range by applying techniques, such as extracting signals from noise in real time, to improve accuracy and repeatability.

Time-Domain Antennas

To measure and locate sources of electromagnetic interference, especially in complex electromagnetic environments containing many sources, both continuous and pulsed, NIST will extend the frequency range and sensitivity of linear antennas, including both active/passive antennas for receiving and passive antennas for transmitting. NIST will study the extension of existing broadband time-domain antennas to 18 GHz. NIST will also investigate the use of increasing antenna aperture by using arrays and parabolic dish antennas as the sensitive elements, to replace the TEM horns of present designs. NIST will apply techniques developed for designing and evaluating receiving antennas to the development of transmitting antennas.

Time-Domain Methods for Whole System Testing

To respond to real-world needs, NIST will develop test methods and, in those cases necessary, supporting instrumentation that permit EMI/EMC testing of complete operational systems in a noisy environment. To achieve broadband characterization, NIST will subject the system under test to a radiated sequence of fast pulses and record the reflected wave (or an induced signal) for analysis. NIST will use this information to inject current corresponding to desired field levels, or to identify natural resonances.

NIST will extend the capabilities of existing time-domain methods and instrumentation, including broadband antennas which have near constant gain and linear phase response from 10 kHz to 1 GHz. These antennas allow for nearly distortion-free transmission and reception of fast pulses and the assumption that the reflected pulses exhibit properties of the system under test, such as an operating military helicopter. In particular, NIST will develop more advanced signal processing algorithms for analyzing the acquired data and a more rigorous understanding of selected theoretical issues. NIST will then carry out demonstrations intended to show advantages of the time-domain approach on a variety of real-world systems.

These efforts will make possible measurements of shielding effectiveness and EM susceptibility that would not be possible otherwise; the testing of large complex systems while operating, generating their own fields, and immersed in external fields. Such characterizations are becoming increasingly important as systems become more dependent upon electronics, the electronic components become more sensitive to interference, and the interference levels increase. Applications range from consumer items such as automobiles, to aircraft, to computer systems, to automated factories. NIST's successful development and transfer of this technology to U.S. industry will provide market advantage and provide powerful tools to address restrictive regulations on emissions imposed by other countries.

TEM Cell

NIST will study two extensions of TEM cell technology for device/system immunity as described above under Project 3.

Reverberation Chamber

In response to requests from the EMC/EMI testing community, NIST will provide a better understanding of the application of reverberation chambers as an immunity evaluation tool by developing underlying theory and conducting and analyzing comparison measurements in a reverberation chamber and in an anechoic chamber. These measurements will be radiative immunity measurements and will concentrate on whole systems. NIST will develop reverberation chambers for immunity testing at high frequencies (above 200 MHz), in particular to expose equipment under test to a complex uniform sampling of incident field directions and polarizations.

NIST also plans to develop a very large TEM line-driven reverberation chamber or hybrid TEM cell/reverberation chamber for the immunity testing of very large systems. Such a chamber would operate as a TEM cell at low frequency and as a reverberation chamber at high frequency. NIST plans a research chamber to evaluate the effectiveness of such a facility to test large systems. A successful outcome will make it possible to test large systems, for example, full-size aircraft, from 10 kHz to 40 GHz in a single facility. If a demonstration facility operates as NIST intends, manufacturers of large systems containing electronics (e.g., cars, small aircraft, mainframe computers) are expected to seek NIST assistance in implementing hybrid chambers in their own test facilities. Smaller and less expensive versions of the NIST-designed should also prove to be a powerful tool for EMC/EMI testing of smaller systems (e.g., televisions, personal computers, stereo equipment) owing to the relative ease of making measurements and the very large frequency range covered by one facility.

Conducted EMI

Conducted EMI is a recognized, pervasive, serious problem that can affect adversely almost any unprotected electronic system connected to other systems by wires, or to 60-Hz power, or both. In response to industry needs, NIST will develop improved methods and techniques for measuring conducted EMI on data and communication lines, power supply lines, and other conductors; means for assessing the effects of conducted EMI, in particular, for assessing the radiated EMI that results from conducted EMI; and methods for relating conducted and

radiated EMI effects. NIST will study the establishment of mathematical and statistical relationships between radiated susceptibility and conducted EMI for selected classes of devices or components.

As industry attempts to satisfy FCC and military requirements for the radiated susceptibility level of electronic components and devices, many tests have traditionally been performed in electromagnetically exposed environments. Generation of the required field levels in the open often causes electromagnetic interference to others. These tests are also themselves vulnerable to EMI. Test sites which minimize these problems are often inaccessible or too costly. NIST intends to develop methods that will inject predetermined currents into a device or system under test in ordinary indoor laboratory space.

Shielding Effectiveness of Materials

To meet needs for consistent, reliable and theoretically grounded measurements of electromagnetic shielding effectiveness (SE) of materials, NIST will develop improved methodology and test methods, in particular to make possible the design of electronic devices and systems having known levels of electromagnetic compatibility. NIST plans to evaluate methods for measuring the shielding effectiveness (SE) of materials, based on the principle of simulating either far-field or near-field environments. For methods based on far-field simulation, NIST will extend beyond existing capabilities the frequency range and the range of permissible sizes of the material test specimen.

NIST will develop two methods for measuring SE of materials, based on near-field simulation. NIST will first study a dual-TEM-cell configuration in which the material test specimen is sandwiched between corresponding apertures in two closely adjacent TEM cells, with emphasis on reducing the contact resistance between the test specimen and the cells. In this configuration, a measurement is made of the amount of energy that couples through the specimen from one cell to the other. NIST will then study a configuration suitable for measurements above 1 GHz, in which a single TEM cell is placed inside a reverberating chamber and a measurement made of the energy that couples into the cell through an aperture covered by the test specimen.

Shielding Effectiveness of Cables, Connectors, and Housings

Since cables, connectors, and housings may contribute positively or negatively to the degree of electromagnetic immunity that a system enjoys, their shielding effectiveness needs to be evaluated. To meet these needs, NIST will develop test methods suitable for evaluating SE in the complicated geometries that are encountered in actual systems. NIST will develop general definitions of SE that will describe the relevant physics and provide a basis for models that can be used to interpret the results of measurements for these geometries. NIST plans to cover a broad range of frequencies from kilohertz to gigahertz. NIST will also study applications of TEM cells and reverberating chambers to cover low and high frequencies respectively, the challenge being to develop a single definition of SE that applies to evaluations in both types of facility. NIST will begin its work on SE measurements for cables and connectors with a configuration that measures EM penetration through a small circular

aperture in the copper shield of a coaxial line. If this approach results in useful methods, NIST will study an analogous procedure for evaluating SE for housings.

Project 5: Special Topics

This section identifies the proposed NIST response to various needs of industry and the EMC/EMI testing community that cannot be classified as falling under any of the four major thrusts discussed above. The topics are harmonization of standards, measurement of electromagnetic fields radiated by electrostatic discharge, characterization of electromagnetic environments, and electromagnetic evaluation of electroexplosive devices.

Harmonization of Standards

To provide simplification of testing requirements and improvements in individual standards, NIST will compare the military standards MIL-STD-461/462 for emissions and immunity testing to various civilian standards, to identify overlap and differences among the different standards, and to recommend changes that would bring them all into agreement. NIST has already compared MIL-STD-461-462 to FCC requirements. Building on this assessment, NIST plans to compare the FCC and military standard requirements to American National Standards Institute standard C-6B and the standards of the Computer and Business Equipment Manufacturers Association, a computer manufacturers' organization whose members must meet FCC requirements to market their products in the United States.

Measurement of Electromagnetic Fields Radiated by Electrostatic Discharges

To respond to serious problems identified by industry, NIST will develop new methods and techniques for measuring the current waveform and the associated electromagnetic fields radiated by broad-band electrostatic discharges (ESD) in order to assess the EMI effect on electronic devices and components. Specifically, NIST will (1) identify a realistic electronic component as a potential victim and to assess the EMI effect on it; (2) make more systematic measurements to develop a fundamental understanding of the electromagnetic issues; (3) investigate the feasibility of designing a corresponding broadband H-sensor for measuring the magnetic fields associated with ESD.

ESD is a common phenomenon with a potential to seriously upset or even damage electronic devices, especially low-powered microelectronic components. For example, the operator of a vehicle having extensive electronic control circuits may immobilize the vehicle when he or she starts to insert the key into the door lock and a spark jumps from key to lock. The consequences may be much more serious. According to a recent disclosure by a major U.S. company, 60% of its electro-optic components did not survive the ESD created at the manufacturing and packing stages. Currently, sample testing by direct injection of ESD is a widespread practice which, together with the prevention of ESD, consumes large amounts of resources by the electronics industry. Considerable effort has gone into the development of ESD simulators for simplifying and standardizing testing. ESD radiated fields have received little attention, mainly because no sensors exist with a wide enough bandwidth for measuring such broadband ESD pulses. NIST will respond to strong needs in developing standard methods for measuring real-time ESD currents and the associated radiated fields.

Characterization of Electromagnetic Environments

To respond to needs to describe a generalized electromagnetic environment, NIST will develop theory, techniques, and methodologies for measuring and characterizing such environments. NIST will study the theoretical description of EM fields in various environments. In particular, NIST plans to concentrate on minimum measurement techniques and to investigate if a specific mathematical procedure, known as a truncated conjugate gradient technique, overcomes the numerical problems encountered earlier. These studies will include the identification and definition of parameters needed to characterize the environment. NIST plans to develop different sets of parameters for different situations, e.g., health hazards, computer equipment EMC, electro-explosive device storage, and signal detection.

ENDNOTES

1. An electromagnetic wave is a wave characterized by changes in electric and magnetic fields with time and location. The frequency of an electromagnetic wave, the rate at which it changes per second, locates it in the electromagnetic spectrum. In the visible portion of the electromagnetic spectrum, frequency corresponds to color. The unit of frequency is the hertz, one event (cycle) per second. For example, in the United States, the standard frequency of utility-generated electric power is 60 Hz. One thousand hertz is a kilohertz (abbreviation kHz); one million hertz is a megahertz (MHz); and one billion hertz is a gigahertz (GHz). The range of frequencies presently of greatest interest to the radio-microwave community extends from a few kHz to over 110 GHz. As an alternative to frequency, wavelength, the physical distance separating two successive maxima, minima, or other corresponding points of the wave, may be used. In terms of wavelength, the range of wavelengths presently of greatest interest to the radio-microwave community extends from 100,000 meters to three thousandths of a meter (i.e., 3 millimeters, hence the term millimeter-wave to refer to the microwave region above about 30 GHz).

2. Ground-screen range (also called open-area test site, open field site) consists of a conducting surface supported on a suitable flat structure in an area determined to be free from electromagnetic interference, at least at the time measurements are made on the equipment under test. The conducting surface determines the electrical ground plane. A common implementation takes the form of metal mesh or screening mounted on the exposed face of a large concrete slab. Care is taken to make sure that there are no conducting structures or surfaces near the range that could reflect electromagnetic energy back towards it. When such a range is being used for emissions testing, the instrument under test and the measuring antennas are mounted at predetermined distances above the ground plane. FCC emissions regulations specify a ground-screen range as one type of facility on which qualifying measurements of computing devices can be made using specified test geometries.

3. As with its acoustic analog, the microwave anechoic chamber is a special room, intended to absorb all the microwave energy incident upon its inside surfaces: walls, floor, and ceiling. Thus, no microwave energy should be reflected back to a source or to any other object in the chamber with the source. The microwave anechoic chamber thus simulates the electromagnetic environment of free space.

4. A TEM cell establishes known planar electric and magnetic fields inside the upper and lower cavities of the cell, which therefore can serve as an electromagnetic environmental test chamber. A TEM cell represents a greatly enlarged section of coaxial line, with the inner conductor taking the form of a septum, or plate, parallel to the floor of the cell and dividing it into equal volumes. The outer conductor becomes a rectangular box insulated from the septum. Tapering transition sections at each end of the box connect it to coaxial connectors. NIST established the TEM cell as a useful measuring tool that is now in the catalogs of a number of companies, frequently under the name Crawford cell, Crawford being the name of the NIST researcher who made major contributions to the use of TEM cells for probe calibrations and emissions and susceptibility testing. For emissions testing, a suspect emitter (e.g., pocket calculator) is placed in one of the volumes of the cell and the resulting distortion of the field is measured with the device operating. A limitation is that device should be small enough not to perturb the field significantly when the device is not operating. For susceptibility testing, a victim device (such as a heart pacemaker) is subjected to predetermined known fields, usually in a number of orientations, and the device operation is monitored. Probe calibrations with the cell are similar to susceptibility tests, with the difference that careful reference-level measurements are made of the probe output. The useful frequency range of TEM cells depends on the intended use; for practical purposes, cells can be made to cover dc to about 150 MHz.

5. Immunity as used in the context of this chapter refers to the capability of a component, instrument, or system to function as intended in the presence of the electromagnetic environments it would encounter in use. Specification for immunity performance include frequency ranges and fields, including field polarizations. Depending on the application, immunity to both continuous and pulsed fields may be needed.

A related term is susceptibility. In the context of this chapter, susceptibility refers to the degree to which a component, instrument, or system is not immune, i.e., the inability of a component, instrument, or system to withstand the effects of radiated or conducted electromagnetic fields.

6. Photonic sensors offer several advantages over electrical sensors. They can be fabricated entirely from dielectric materials such as glass and plastic and are thus immune to induced EMI in the cables and circuitry, at the same time producing minimal perturbation of the field being measured. Unlike electrical sensors, the response of a photonic sensor is also insensitive to the arrangement of the signal cables leading from the sensor to the readout instrumentation. NIST expects these features to make photonic sensors nearly ideal transfer standards. The large information carrying capacity of the electro-optic system allows one to preserve frequency, amplitude, and phase information in the signal from the sensor. Thus, photonic sensors can be used to measure complex wave forms, field direction, and frequency content. These capabilities are needed now to characterize complicated EM environments. Photonic sensors also have the potential to meet needs by Department of Defense agencies and contractors in facilities used to test the susceptibility of equipment to electromagnetic pulses. The dielectric materials used in photonic sensors mitigate corona discharge and arcing which disrupt measurements made with electrical sensors. The light weight and low attenuation of the fiber optic cables make them ideally suited for field testing of large systems where long distances between the test objects and the readout instrumentation may occur. Advanced EO modulators based on integrated optics technology have been shown to be capable of operating to at least 40 GHz and are projected to go higher.

7. A reverberation chamber is an electromagnetic environmental test chamber in which the desired environment is a distribution of electromagnetic energy in as many electric, magnetic, and electromagnetic modes as possible throughout the physical volume of the chamber and over the frequency range of interest. Sometimes the distribution of modes is enhanced by a large fan-like rotating structure, which has the same effect as that of the mode-stirring fan in a microwave oven.

Chapter 11 NIST'S ROLE IN MEASUREMENT DEVELOPMENT

Approaches to Federal Support for Technology

The Government uses many approaches to stimulate progress in technical fields and to promote U.S. international competitiveness. Among them are these:

The Government funds and conducts technical work itself, as it does in the national laboratories of the Department of Energy and in other Government laboratories.

The Government funds others to do technical work, as it does through the grants of the National Science Foundation and through the contracts provided by many other Government agencies.

The Government provides partial funding to others to do technical work, as it does through research tax incentives.

The Government provides tools to others who fund and do the technical work.

This last approach is the one that NIST employs when developing and providing measurement capability. The "tools" are various forms of measurement capability that directly foster technological progress. This measurement capability is delivered primarily in the form of information. Information has high leverage because, unlike funding, is not subdivided during distribution. Thus it can be provided to many users with full effect. Further, this information complements and strengthens all of the other Government approaches by providing measurement tools needed for the conduct of the work that they support.

NIST Measurement Capability

NIST measurement capability takes three principal forms: measurement methods, measurement standards, and measured data.

Measurement Methods

The measurement methods that NIST develops are those that are especially important to industrial progress and that are especially difficult to develop. Most often these are new measurement methods; they are often needed to provide greater accuracy than present measurement methods. In other cases, NIST works with existing measurement methods to improve them, or to validate their accuracy, or to resolve differences among competing methods in use in industry.

Measurement Standards

The measurement standards that NIST develops are national reference standards. They are physical objects used to assure the accuracy of the nation's most critical measurement methods. The standards can take several forms. For example:

They may be materials with a precisely controlled property, such as a silicon wafer with a precisely known resistance to the passage of electricity.

They may be electronic devices, like the new national standard for voltage which has been implemented as a superconducting integrated circuit.

Measured Data

The measured data that NIST develops are produced with NIST's advanced measurement capability. Industry needs such data for reference purposes, particularly for materials properties. For example, one of the most urgent needs in industry right now is for measured data that describe how materials interact with microwaves. Such information is essential to the development of microwave integrated circuits and microwave antennas.

Impact of NIST's Measurement Capability

NIST's measurement capability affects virtually every phase of research and development, manufacturing, market transactions, and use of the nation's high technology products. This wide range of impact is another reason for NIST's high leverage.

Research and Development

In the area of research and development, advanced measurement capability promotes the discovery of new physical effects that later become the basis for new products. Without superb measurement capability, the new effects might be missed entirely or might not be understood. Further, good measurements accelerate the process of discovery by enabling the scientific community to reach definitive conclusions quickly. After discovery, advanced measurement capability is often required to optimize the performance achieved with a newly discovered effect. Later, advanced measurement capability is needed to design the products that exploit the new effect.

These several benefits of advanced measurement capability improve the chances of success of research and development, and they reduce the cost of conducting research and development.

Note that NIST's role is enabling not directive. NIST provides measurement capability that industry uses to develop the products that industry chooses. NIST role is not to tell industry what products to develop.

Manufacturing

Once a product has been developed, special measurement capability is required to design manufacturing processes and to control quality during those processes. For example, precise measurements of the widths of the hair-thin interconnecting electrical lines within integrated circuits are essential to controlling the quality of those circuits.

In some cases, just the cost of making the measurements -- aside from the impact of making them well -- is very high. For example, twenty percent of the cost of producing optical fibers is in measurements. Thus the cost of manufacturing is directly affected by the level of available measurement capability.

Market Transactions

When virtually any high technology product is brought to market, its fate in the marketplace is greatly affected by available measurement capability. For example:

Available measurement capability determines whether the performance of a product can be specified in a form useful to buyers.

Available measurement capability determines if sellers can prove to buyers that a product really performs as well as claimed. Without such proof, sales often cannot be completed.

Available measurement capability determines if sellers can prove the compatibility of a product with other products in buyers' systems.

In some cases, the performance and compatibility of products are subject to international regulations which restrict product entry. Special measurement capability may be needed to prove compliance in order to gain entry to the market.

Thus the level of available measurement capability affects the ability of U.S. manufacturers to enter international markets, the ability of buyers and sellers to reach agreement on product performance and compatibility, and the cost of reaching that agreement and completing the transaction. All of these functions are essential to the efficient functioning of a free market on both a domestic and an international scale.

Often the industry's call for NIST measurement assistance becomes loudest during this marketing stage. For example, NIST was recently asked by industry to examine two competing measurement methods used in the marketplace to measure the same property of optical fibers (numerical aperture). The two methods were giving different results, confusing buyers and sellers and impeding commerce. NIST examined the methods, identified the discrepancies, showed how to use the methods in a consistent manner, and thus resolved the problem.

Use

After the sale of a product, measurement capability is often required for the installation and maintenance of systems to assure proper performance. Thus the cost of use is directly affected by the quality of available measurement capability.

Time of Introduction

Because new measurement capability affects all four stages of product realization, the impact of new measurement capability is maximized when it is introduced as early in the product development cycle as possible.

International Competitiveness

The impact of good measurement capability on international competitiveness can be readily summarized. U.S. products cannot compete successfully in the international market without a high performance-to-cost ratio, high quality, demonstrable compatibility with other products and systems, and access to international markets. Accomplishment of these aims is highly dependent on the quality of available measurement capability.

Why Industry Needs NIST

NIST does not develop measurement capability that industry can provide for itself. Rather, NIST focuses on selected measurement problems whose resolution requires NIST's special capabilities or position and whose resolution will have especially high impact.

There are three principal characteristics of NIST which -- taken together -- enable NIST to do what industry cannot do or does not do.

First, NIST's impartiality is widely acknowledged. NIST is not a buyer or a seller, and NIST has no biases that favor buyers or sellers. NIST is not a regulatory agency and thus poses no threat to industry. NIST protects proprietary information.

Second, NIST's competence in measurement capability is widely acknowledged by U.S. industry, by domestic and international customers, and by international regulatory organizations whose rulings affect the access of U.S. products to international markets.

Third, NIST bears the official imprimatur of the U.S. Government as the lead agency for measurements.

These three characteristics combine to give NIST two capabilities critical to its role: access and acceptance.

Access

"Access" means access to industry's internal data and to knowledge of industry's true measurement problems. This access is necessary to define the measurement problems that are afflicting companies broadly. Individual companies will share data on their internal measurement problems with NIST. But individual companies will not readily share such with other companies, so the pattern associated with a given measurement problem might not even be recognized without NIST.

"Access" also means access to industry for testing measurement solutions that NIST develops. NIST is trusted by industry to conduct competent tests and to preserve data that are proprietary to individual companies during the process. Such tests are essential in demonstrating that the measurement problems have really been solved.

Acceptance

The second factor is "acceptance". Once NIST has developed and tested new measurement capability, the full benefits can be realized only if that capability is adopted by industry, by domestic and international customers, and sometimes by international regulators. All three of the qualities of NIST mentioned above -- its impartiality, its competence, and its official U.S. imprimatur -- are essential to achieving such acceptance.

Long Term View

NIST's long term view is also important. NIST's long term view enables it to look far ahead and anticipate measurement problems that must be solved to enable realization of the next stages of technological progress. NIST's long term view is also reflected in its staying power in solving difficult high impact measurement problems and in pursuing industrial adoption of the solutions.

Cost Efficiency

NIST achieves high cost efficiency in the development of measurement capability. NIST expends resources only once to develop a measurement method that is then used by everyone. Far fewer resources are required than the sum total of the resources that individual organizations would expend to duplicate such work, even if they could. This advantage is an additional reason for NIST's high leverage on the economy.

Marketplace Measurements

There are specific reasons why individual companies are not motivated to substitute for NIST in providing measurement capability for the marketplace in particular:

First, they must focus on the needs of their own product lines. They are not motivated to develop measurement capability that applies over industry-wide product types and performance levels, as NIST does.

Second, to provide measurement capability for use in the marketplace, they must inevitably reveal that capability to others, including their competitors, who then receive the benefits of the development without sharing in the costs.

Third, to gain acceptance of their measurement capability in the marketplace, they must incur costs beyond those required to use the capability for their own internal research and development.

Thus, while the mission of NIST is to provide measurement capability that serves all companies, this is not the mission of individual companies.

Delivery

NIST focuses a very large portion of its energy on the delivery of the measurement capability that it develops. Delivery is accomplished in several ways: communications, joint activities, and paid services.

Communications

NIST communicates its findings to wide audiences through published descriptions of virtually all of its measurement capabilities, through talks at conferences, and through telephone consultations with industry, Government agencies, and universities.

Joint Activities

NIST engages in a variety of joint activities with industry. NIST staff participate in industrial associations and professional societies. These organizations incorporate NIST measurement capability into voluntary industry standards. This is a very important method of promoting adoption of improved measurement capability. Federal and state agencies further adoption by requiring that the products they purchase, or that they regulate, be evaluated or calibrated with the measurement capability that NIST has developed. For example, both the Department of Defense and the various state public utility commissions require traceability to NIST measurements.

NIST conducts round robin measurement comparisons with industrial and Government participants. In a round robin, NIST circulates a physical object, such as a special optical fiber, to the organizations that wish to participate. They measure carefully certain important properties of that object, and they report their findings in detail to NIST. By studying the results of the measurements, NIST can determine if a new measurement method is needed. If so, NIST develops that method and trains industry and Government representatives in its use. Then NIST conducts a second round robin to assure that all of the participants can measure the important properties accurately.

NIST also conducts cooperative research projects with industry and with Government agencies. Employees from participating organizations come to NIST to work with NIST staff for six months to two years. This is one of the most effective methods for transferring measurement technology.

Paid Services

NIST also provides special measurement services to individual companies and to Government organizations that pay for those services. This type of support takes many forms:

Other agencies transfer funding to NIST to support development of custom measurement capability needed for their specific systems.

NIST sells copies of NIST-developed physical measurement standards needed by industry or by Government agencies for on-site verification of their measurement capability.

NIST calibrates measurement standards that industry and Government agencies send to NIST for that purpose.

NIST provides courses that train industry and Government staff in the use of advanced measurement capability.

Beneficiaries

These means of delivery touch a very wide range of beneficiaries including companies, Government agencies, universities, and individuals. The beneficiaries function in many different capacities -- as sponsors or performers of research, as manufacturers, as buyers, as users of services, or as regulators. This broad audience is a further reason for the high leverage that NIST achieves.

Who Pays for NIST?

The broad range of beneficiaries helps to explain why NIST is funded in the manner that it is. NIST uses direct appropriations, paid for by all beneficiaries through the tax system, for the development of fundamental measurement capability that benefits everyone. This fundamental measurement capability includes measurement methods, measurement standards used at NIST, and measured data.

When NIST is developing special measurement support for specific beneficiaries, or when NIST is incurring costs to deliver developed measurement capability to individual users, then NIST charges the immediate beneficiaries for the costs. Examples of special measurement support include custom measurement development, measurement standards delivered to specific beneficiaries, calibration services, and training courses in measurement methods.

NIST's High Leverage

The above discussion suggests how NIST's measurement role gives NIST high leverage in promoting technological progress and international competitiveness in the U.S.:

NIST measurement capability is primarily in the form of information. Information, unlike funding, is not subdivided during distribution and thus can be provided to all users with full effect.

NIST measurement capability serves a broad audience, composed of industry, universities, Government agencies, and individuals, in their several roles as manufacturers, buyers, researchers, regulators, and users of services.

When NIST develops measurement capability, the cost of development is paid for only once, not over and over again, as individual companies would have to do, even if they could develop such capability independently.

NIST measurement capability advances all stages of product realization, including research and development, manufacturing, market transactions, and use. NIST focuses on the highest impact measurement problems that affect such product realization.

Finally, NIST measurement capability multiplies the effectiveness of other Government programs for stimulating the development of technology. NIST does this by providing measurement capability critical to the conduct of those programs.

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Powerful technologies are emerging in many fields of electronics. They promise new generations of products with higher performance and lower cost. U.S. success in realizing products from these emerging technologies is vital to U.S. competitiveness in key world markets. U.S. competitiveness requires a high level of supporting measurement capability. That capability affects every phase of product realization: research and development, manufacturing, marketing, and use.

The National Institute of Standards and Technology (NIST) is the nation's lead organization for the development of measurement capability and for the maintenance of national reference standards that assure the uniformity of that capability. Within NIST, the Center for Electronics and Electrical Engineering (CEEE) is responsible for measurements that support the U.S. electronics industry. As part of fulfilling this responsibility, CEEE assesses measurement needs that affect the competitiveness of the U.S. electronics industry in emerging technologies. This report is the second in a series that seeks to provide an increasingly comprehensive assessment of those needs. Through issuance of this report, CEEE seeks feedback from U.S. industry and from Government agencies to help refine the assessment of those needs and to guide future programs of measurement support responsive to those needs.

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