An Assessment of the United States Measurement System:

Addressing Measurement Barriers to Accelerate Innovation

Appendix B

Case-Study Measurement Needs: A Compilation

NIST Special Publication 1048

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

Introduction

This assessment of the U. S. Measurement System is based upon data, termed measurement needs. These are defined as unsolved industry measurement problems that pose technical barriers to economically important technological innovations and were identified and documented using several methods:

- Industry technology roadmaps,
- Workshops, some sponsored as part of this assessment effort,
- Synthesis by NIST staff from various combinations of industry reports, technical publications, and interviews, or
- Submitted by individuals representing organizations found in the private sector, or other federal, state, or local governments.

All were documented. Measurement needs from the latter three sources were documented according to a uniform, one-page, case study format that are stand-alone discussions of a particular measurement barrier to technological innovation. Three hundred twenty two if these case studies were produced for this assessment from fall 2005 to spring 2006 and are found in the latter portion of this appendix. Of these 68 have been derived from the deliberation of NIST-USMS-sponsored industry workshops, and 10 were submitted by industry organizations or by other Federal or State agencies.

Authentication of the Factual Basis of Case Studies

These case studies contain assertions concerning the facts surrounding a particular measurement issue that poses a real or potential problem or impediment to technological innovation. A process was established to verify or validate the facts presented in a case study and has been termed authentication. Authentication is the confirmation that information contained in individual measurement needs case study documents is factual and an accurate summary of the subject matter. Several means are available for authentication of Measurement Needs. Documentation sources used may be:

- Public documents
- Workshops – publicly available reports, or USMS-sponsored workshops which had documetnation requirements for scope of discussion and requirements for a broad representation of view in the topic of interest.
- Published technology roadmaps
- Industrial representative – In some cases letters from industrial representatives were obtained as documentation of the authenticity of the case study.

In most instances, authentication documents discuss and summarize the public domain, documentary references used, specifically referring to key facts and major assertions that are presented in various sections of the case study.

Measurement Needs Case Study Template

Each measurement needs case study was required to adhere to a template of specific format. An example was provided, which is shown on the following page, as a guide to both the form and content expected of each case study. Upon receipt of a case study by the USMS task group, it was reviewed for content and clarity of exposition before being accepted.

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Case Study – Measurement Needs With Some Cues and Clues on Types of Responses

Technology at Issue: *[2-3 words: as broad or as narrow as fits situation]*, e.g. one of following: Nanotechnology for Advanced Materials; Molecular Self Assembly; Spectroscopy of Proteomics; Construction Automation

Submitter: Jane Researcher [no affiliation given unless for non-NIST submitters]

Technological Innovation at Stake: *[What the specific technological change, i.e. new technology, that is being anticipated, considered, or attempted, by whom, in what field, firm, sector to what end?]* Pharmaceuticals manufacturers anticipate the use of molecular self assembly for their manufacture of Z-type nanoparticle drug delivery systems. Early-adopters in the construction industry have begun using GPS-guided robotic graders.

Economic Significance of Innovation: *[What costs will be incurred if innovation inhibited. What is the return on investment for the implementation of the innovation? Some examples might be quantifications of cost savings, product development time, acceleration of innovation that opens a lucrative window of opportunity…]* Acceleration of process time enables a cost reduction to industry, and because of the cost competitive nature of the industry, the cost reduction will be passed to the consumer. This will also enable the ability to produce more targeted drugs in smaller batches…

Technical Barrier to the Innovation: *[Why can't the innovation be reasonably implemented now or when desired? What technical barrier is in the way?]* The basic phenomenon of self-assembling in this particular class of macromolecules is only partially understood with unpredictable variations of behavior occurring. Absence of technical data on performance of materials in cantilevered MEMs devices inhibiting development of desired new type of sensor. Customer uncertainty about unverified capabilities of competing types of first generation laser-mapping-guidance systems is impeding acceptance of this technology.

Stage of Innovation Where Barrier Appears (R&D, Production, Marketing, End Use): *[choose one]*

Measurement-Problem Part of Technical Barrier: The investigation of the not-well-understood interactions of constituents in self-assembling macromolecules requires time- and spatial-resolutions of measuring instruments beyond current state-of-the-art. There is an absence of a trustworthy reference measurement protocol for evaluation of performance the new-generation laser-mapping-guidance systems.

Potential Solutions to Problem: R&D to find practical way to finesse the capabilities of current measurement instrumentation. Development and commercial introduction of new class of instruments is needed to expand knowledge of the mechanisms controlling chemical self assembly of X on Y surfaces.

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Case Study Index by Economic Sector / Technology Area

Agriculture and Food Processing

Building and Construction – Residential/Commercial Building

Building and Construction – Civil Infrastructure

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Case Study Index by Economic Sector / Technology Area

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Case Study Index by Economic Sector / Technology Area

Energy and Power – Nuclear

Environment

Healthcare – Bioimaging and Informatics

Healthcare – Clinical Diagnostics

Healthcare – Health and Safety

Healthcare – Pharmaceuticals

Homeland Security – First Responders

Industrial Biotechnology

Manufacturing – Continuous

Materials – Ceramics

Materials – Metals

Materials – Polymers

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Case Study Index by Economic Sector / Technology Area

Measurement Technology – Instrumentation

Measurement Technology – Process Control

Measurement Technology – SI Units

Nanotechnology

Telecommunications

Transportation – Aerospace

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Case Study Index by Economic Sector / Technology Area

Transportation – Automotive

Other – Law Enforcement

Other

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Case Study – Measurement Needs

***Technology at Issue*:** Fuel Flexible, High-Efficiency and Low Emission Power Systems

***Submitter*:** Jeffrey Manion

***Technological Innovation at Stake*:** Next generation power system fuel flexibility is critical for use of alternative domestic, fossil fuel sources, e.g., tar sands and coal, while achieving more efficient and less polluting combustion. Such fuels, which differ significantly in chemical composition and structure from current fuels, may well be the dominant combustion fuels of the future.

***Economic Significance of Innovation*:** Fossil fuels power US transportation - with a conservatively estimated fuel cost of over $300 Billion each year. Incremental increases in efficiency of diesel, gasoline and jet engines directly and proportionately impact the U.S. economy. Adverse health effects stemming from combustion-derived pollution incur a significant portion of national health care costs. In addition, secondary chemical reactions arising from pollutants adversely affect food production and degrade building materials. Finally, more fuel-flexible, efficient combustion technologies reduce the need for imported oil, thus having significant benefits relating to national security and the economy.

***Technical Barrier to the Innovation*:** Accurate combustion models depend strongly upon the fuel's chemical composition and are an important contributor to advanced power system design. The physical and chemical data necessary to validate combustion models or to extend them to the use of these new fuels are not available. This limits power system producer's ability to design new systems and creates high costs and unacceptably high risks in committing to new technology.

***Stage of Innovation Where Barrier Appears*:** Research and Development

***Measurement-Problem Part of Technical Barrier*:** The physical and chemical data needs for simulations of the combustion of fuels are twofold: a) all existing data relevant to combustion modeling must be made available so that researchers and designers across the necessary scientific disciplines can readily engage in collaborative development of simulations, and b) methodologies must be developed and validated to simulate complex real fuel mixtures and extend the existing knowledge base to fill key data gaps.

***Potential Solutions to Measurement Problem*:** A NIST sponsored workshop on this subject held in September 2003 involving industrial, academic, and government agency scientists/program managers identified three main developments to address the technical barriers and measurement needs. Well-defined surrogate fuel mixtures that match the appropriate chemical and physical properties of gasoline, diesel, and jet fuels must be developed to deal with the complexity of real fuels. Data gaps in the physical and chemical properties of the surrogate systems need to be identified and filled (from theory and experiment). A central data depository for collecting, evaluating, and sharing all relevant combustion information, existing and new data, must be developed. It is broadly recognized that the latter is a pre-requisite to the former two developments and to success in meeting goals of all parties.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Next Generation Electrotechnical Products, Components, and Raw Materials

***Submitter*:** J. R. Sieber

***Technological Innovation at Stake*:** The RoHS, Restriction on Hazardous Materials, regulations recently adopted by the EU and other U.S trading partners impose significantly reduced maximum allowable concentrations of cadmium, mercury, lead, hexavalent chromium, and certain brominated flame-retardants in electrotechnical products. Current and future products and components, and their raw materials, are affected. Companies seeking market entry for consumer electronic and electrical products require stringent materials declarations from their suppliers at all levels of the supply chain.

***Economic Significance of Innovation*:** Some current raw materials will require significant reduction in proscribed compound content and new ones developed. RoHS regulations affect the worldwide market for electrotechnical products and their entire supply chain, a multi-$100 billion dollar per year market. U.S. companies are significant exporters and must comply by replacing components and designing new manufacturing processes to accommodate new or modified raw materials. Documentation of hazardous materials content is required to demonstrate compliances with RoHS requirements.

***Technical Barrier to the Innovation*:** Internationally recognized standards for documentation of supply chain compliance with RoHS regulations are needed. Proposed product safe lifetime labeling requirements are anticipated that will require implementation of new concepts and testing methods for materials degradation testing. New standardized analytical test methods and certified reference materials are needed to ensure that both raw materials and finished goods are compliant with the RoHS regulations.

***Stage of Innovation Where Barrier Appears*:** Marketplace

***Measurement-Problem Part of Technical Barrier*:** New test methods, and the concentration standards supporting them, are needed for raw materials, intermediate and finished goods. New or improved measurement methodologies and standards to support materials content compliance and product lifetime claims are needed. The global market requires international recognition of new test methods and content standards.

***Potential Solutions to Measurement Problem*:** Broad/International acceptance of measurements and standards supporting material content declarations, test methods that measure concentration of the RoHS substances in raw materials, intermediates, and finished products; new lifetime testing methods and the scientific/technological base supporting them, and certified reference materials (CRMs) pertinent to the methods and materials of test.

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Case Study – Measurement Needs

***Technology at Issue*:** Serum-Based Proteomics for Early Cancer Detection

***Submitter*:** P. Barker, D. Bunk

***Technological Innovation at Stake*:** The lack of reliable, high throughput diagnostic test methodologies for identification and quantification of proteins and peptides in human serum inhibit effective early cancer detection strategies. The appearance and concentration of specific proteins and peptides in human serum has been demonstrated in limited clinical trials to provide analytes for early cancer detection. Protein and peptide analyses of human serum, serum proteomics by clinicians, require reliable, specific measurement methodologies that distinguish cancer-based bio-analytes from those found in healthy individuals. Healthy human serum is highly chemically dynamic and complex. Protein concentrations range over 10 orders of magnitude from the most common (albumin) to diagnostic molecules like the interleukins.

***Economic Significance of Innovation*:** It is not possible to estimate the overall fiscal and heath cost of delays in diagnosis of cancer, or of inaccurate laboratory testing of serum markers. In addition to healthcare providers, a breakthrough in serum proteomics measurement capabilities would have significant impact for federal healthcare research, for third party reimbursement agencies that bear the costs of inaccurate testing, for instrumentation manufacturers and for large pharmaceutical companies who use serum proteomics to follow drug effects of their new experimental drug treatments.

***Technical Barrier to the Innovation*:** After much effort and expense by the private sector and federal agencies, it is clear that continued progress toward reliable diagnostic testing is heavily dependent upon comparability of diagnostic measurement results across laboratories. Although initial serum proteomics efforts on control (healthy) and diseased patients have identified serum biomarkers for very early cancer detection, e.g., ovarian cancer, these capabilities are limited to single clinics and are not broadly extendable either to other healthcare facilities or the full range of cancers found in humans.

***Stage of Innovation Where Barrier Appears*:** Marketplace

***Measurement-Problem Part of Technical Barrier*:** Comparability of measurement results requires reliable, widely accessible, and accepted measurement and procedural methods and standards. Identification standards for mass spectrometry, a potential serum protein analysis workhorse, don't exist. Clinical serum sample preparation methods (variability of time, temperature, containment method, use of preservatives, etc.) require significant improvement. Improved detection methods, e.g., affinity-based technologies, a likely future diagnostic platform, can address the broad range of analytes needed to address all cancers found in humans.

***Potential Solutions to Measurement Problem*:** Standards for reliable protein and constituent peptide identification can support both clinical testing to identify new cancer markers, and for their routine detection in standardized clinical formats and platforms. Once identified, the standardized procedural methods are required for diagnostic-testing laboratories use. New diagnostic methods for early cancer detection capabilities are needed.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Microarray Gene Expression Profiling

***Submitter*:** M. Salit

***Technological Innovation at Stake*:** DNA Microarrays can be powerful tools for inexpensive (~US$500) genome-wide experiments to survey gene-based activity for disease diagnosis. The gene expression profile, i.e., which genes are active and at what magnitude, of a cell contributes strongly to its unique nature and properties, enabling different cells that contain identical genetic information to have many properties. A DNA microarray simultaneously measures the activity of as many as ~50,000 genes, and, as such, are anticipated to have a critical role in expansion of genomic and personalized medicine. Reliable microarray results will enable pharmacogenomics, where genomic measurements are used for informed drug selection, design, and dosing, resulting in improved safety and efficacy.

***Economic Significance of Innovation*:** The DNA microarray is currently not approved by FDA for clinical use, therefore is limited to the research market, valued at ~US$500 million in 2005. Use as a clinical diagnostic method can have a large impact as a diagnostic device for physicians, a a market increase of several fold (>$1 Billion). Presently, the lack of a technical infrastructure supporting measurement result validity limits acceptance for clinical use. An accepted measurements infrastructure would improve microarray result validity and improve FDA's ability to accept and effectively regulate these products and providing an enabler for pharmacogenomics to pinpoint more efficacious drug use. Currently a cost of about $1B is incurred from development through FDA acceptance.

***Technical Barrier to the Innovation*:** Approval of microarray gene expression for clinical use requires presentation of objective evidence of necessary levels of sensitivity, specificity, reproducibility, and accuracy. This requires measurement standards and methods that currently do not exist. Discordance of reported results from microarray studies, and difficulties in reproducing study results, has made it difficult to establish reliable correlation of a measured gene expression profile with a biological state or treatment outcome. This discordance and irreproducibility can only be addressed through a more complete understanding of the measurement, and is essential for acceptance for clinical use.

***Stage of Innovation Where Barrier Appears*:** R & D

***Measurement-Problem Part of Technical Barrier*:** No standardization infrastructure exists to validate DNA microarray results. In its absence, a more complete understanding of the sources of measurement problems and uncertainty is greatly impaired, and demonstration of the linkage between device results and biological states and outcomes is impossible.

***Potential Solutions to Measurement Problem*:** An improved knowledge base, measurement standards, reference data, and predictive models will support a validation path for microarray technologies. Various elements of microarray function, nucleic acid chemistry and hybridization; variability of microarray signals; microarray performance; and informatics for managing the massively parallel data are needed. Quantitative understanding of these elements enables quantitative measurement uncertainty analysis as the basis for the technical infrastructure development supporting measurement validation and accuracy.

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Case Study – Measurement Needs

Technology at Issue**:** Measurements and Standards for Genetic Testing

Submitter**:** J. Jakupciak, K. Richie

Technological Innovation at Stake- Clinical laboratories in the molecular genetic testing (MGT) industry utilize microarray technologies to identify DNA sequences associated with genetic diseases and have begun using residual patient specimens as quality control materials in their laboratory practice. As MGT becomes widely available, the number of tests for inborn and acquired errors in human genes is anticipated to accelerate, especially in light of the rapid rate of gene discoveries linked to disease states and the demand for improved quality of life for both the aging population and for newborns.

Economic Significance of Innovation**:** The MGT market grew from $320 M in 2000 to $778 M in 2005, consistently exceeding 20%/yr. The increase in MGT is fueled by the advent of personalized medicine, discovery of disease biomarkers, and the pace of technological advances applied to the diagnosis of symptomatic individuals, carrier screening, prenatal testing and newborn screening provided by a growing number of private companies. Early diagnoses based on genetics can make medicine much more efficacious than is currently possible. For example, MGT can identify which patients will be more likely to respond to drugs than others, thus creating drugs that are more effective, and simultaneously makes drug development cheaper (by simplifying clinical trials).

Technical Barrier to the Innovation**:** Development and acceptance of common methodologies and protocols supporting quality control remains an unmet challenge. MGT has moved from academic research into the marketplace and has recently been mandated in all states for certain diseases. There is great concern that inaccurate and erroneous tests have resulted in unwarranted intervention, overestimation of biomarker present, or misdiagnosis, misclassification of a biomarker(s). These drive the need for effective quality assurance controls and demonstration of comparability of results across the laboratory system. Although MGT laboratories continually provide new tests, certified standards are needed to support test result validity. Many laboratories develop and use their own reference materials further aggravating the inability to compare results among laboratories..

Stage of Innovation Where Barrier Appears**:** Marketplace

Measurement-Problem Part of Technical Barrier**:** Few well-characterized materials suitable as standards supporting quality control, inter-laboratory comparability of MGT results, and laboratory proficiency testing currently exist. Improved measurements of a wider spectrum of biomarker purities and quantities require development to promote a common, reliable, and broadly accepted genetic testing.

Potential Solutions to Measurement Problem**:** Well characterized, widely available, and renewable synthetic materials that accurately mimic the clinical equivalent material for use to standardize results and evaluate performance are needed. Laboratory accreditation programs are needed for proficiency demonstration and will rely upon readily available, certified reference materials to demonstrate laboratory proficiency. Continued developments in the science and technologies are needed address additional diseases.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Solid-State Sensors for Chemical Analysis of Complex Gas Mixtures

***Submitter*:** S. Semancik

***Technological Innovation at Stake*:** Low cost, low operating power technologies for real-time chemical analysis of gas and vapor mixtures are needed in applications ranging from human breath analysis to toxic gas detection. Solid-state technology approaches have good potential to meet these requirements and revolutionize gas mixture analysis because their low cost has such broad application potential. Low power consumption and good sensitivity combined with portability will enable such real-time, point-of-use applications, e.g., toxic industrial compounds, chemical warfare agents, disease state diagnosis based on human breath analysis, composition variations of gas streams in industrial processes, vehicle exhaust analysis, etc.

***Economic Significance of Innovation*:** Real-time, cost-effective analysis of complex, multi-component gas mixtures is a pervasive measurement need for industrial (chemical, petrochemical, semiconductor, and pharmaceutical.), government (defense, climate change), and public welfare applications (homeland security, health care). The market for widespread deployment chemical warfare agents or toxic industrial chemicals detection technologies alone is conservatively estimated at $1B. Health care savings of up to $20B/yr have been estimated for effective breath analysis diagnostics for convenient, at-patient screening diagnostics for early/treatable disease states such as diabetes and metabolic disorders. Innovative, rugged, reliable, low power gas mixture analysis technologies could significantly expand the current $2.9 B chemical sensors market.

***Technical Barrier to the Innovation*:** Multi-component gas mixture analysis using solid-state sensor technology strategies require sensor arrays having individual array elements with known and variable sensitivities to mixture components. Array fabrication and thin film transduction utilizes several relatively new, challenging, complex technologies, e.g., Micro-Electro-Mechanical Systems technologies. Predictable tuning of individual element response characteristics must be coupled with complex data analysis methods. However, data analysis algorithm complexity coupled with issues of limited sensitivity, accuracy, and long-term stability of the individual sensor array elements hinders the widespread adoption of microsensor technologies.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Reliably design for sensitivity tuning of array elements to achieve optimal sensitivity and selectivity for specific applications is needed. Currently this is primarily an empirical, time-consuming, trial-and-error process. A broader knowledge base better describing adsorption and fouling phenomena is needed.

***Potential Solutions to Measurement Problem*:** R&D on absorption/desorbtion/fouling mechanisms in thin films is need to support reliable design of sensor array element function. In addition, R&D directed toward determining the uncertainties and robustness of the microsensor signal processing routines under a variety of well-defined chemical exposure events and conditions is needed.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Molecule-Based Nanoelectronics

***Submitter*:** C.D. Zangmeister/R.D. van Zee

***Technological Innovation at Stake*:** Component miniaturization and new materials are needed to meet the ever-increasing speed and power requirements of computers. However, the CMOS field-effect transistor, engine of the modern computer, is forecast to reach performance limits some time between 2010 and 2015. Further reduction in component size will require new technologies that complement and enhance CMOS devices. Manufacturers are developing strategies to integrate molecule-based nanoelectronic ("moletronic") components into memory and computing circuits.

***Economic Significance of Innovation*:** Computer processor production is a $200 billion/yr industry and is projected to grow to $500 billion/yr by 2010. This growth depends on innovation that increases processor speed, efficiency, and reduces fabrication costs. The development of molecule-based component technologies will enhance the pace of innovation of new processors, as well as cut production costs by reducing the number of fabrication steps. Moletronic devices have already been demonstrated to make ultrahigh density memory (100 GB cm^{-2}). In 2005 dynamic random-access memory sales were $30 billion, and if scale-up can be achieved, moletronic memory devices are expected to dominate that market.

***Technical Barrier to the Innovation*:** While many promising device prototypes have been demonstrated, yield and reliability remain key barriers to commercialization of moletronic devices. These fabrication difficulties can often be linked to the lack of reproducible and reliable methods for measuring the electrical performance of fabricated devices. New approaches to measurement of molecular-scale electrical behavior are critical to successful realization of such molecule-based components. Such approaches also support the performance evaluation of prototype device structures and materials in device/component development.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** Conventional test and measurement devices and approaches are inadequate and, many times, inappropriate to molecule-based components. For example, it is often unclear whether the measured electrical characteristics of a moletronics circuit are linked to the way a particular measurement is made or to actual device performance. Such ambiguity clouds interpretation of basic measurements and slows innovation. It could be eliminated with reference data for performance of prototypical molecular components in a validated test-bed. New tools and methods for measuring electrical properties at the molecular level are required for reliable and reproducible measurements in robust manufacturing.

***Potential Solutions to Measurement Problem*:** New measurement tools capable of characterizing molecular electronic structure, the electrical behavior of small number of organic molecules will serve both production and R&D needs. These tools must be validated against prototypical molecules and devices. Reference data and materials will be required to calibrate and maintain these instruments.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Inhalation Insulin Delivery /Diabetes Management

***Submitter*:** N. Ritchie

***Technological Innovation at Stake*:** Metered delivery of insulin, similar to inhalers for the treatment of asthma, in which insulin is inhaled directly into the lungs. Insulin inhalation from a metered device could substantially improve patient management of blood sugar levels, likely leading to significantly improved patient health and substantially reducing the cost of diabetes-related complications.

***Economic Significance of Innovation*:** Over 20 million people in the United States have diabetes and over 200 thousand people a year die from diabetes-related complications. About one in every ten healthcare dollars is spent on diabetes-related ailments, and it was estimated that in 2002 the total economic cost of diabetes was $132 B, with about 70% of this cost due to direct medical expenditures. A large fraction of these dollars is spent to mitigate the complications resulting from poor management of insulin levels. The standard treatments rely on unpleasantly invasive methods of insulin dose management based upon either subcutaneous injection or an insulin pump. Studies show that only one-third of diabetic patients 65–74 years of age requiring insulin injections maintained recommended dosage levels. Indeed, it is thought that inhalable insulin has the potential to substantially or completely replace injectable insulin treatments.

***Technical Barrier to the Innovation*:** The FDA and the pharmaceutical industry have strict standards regulating the production and quality control methodologies in the manufacture of pharmaceutical products. Inhalation of contaminating particulates directly into the lung constitutes a potential health hazard to users. Micron-sized metallic particles can be mixed at very low concentrations with powered insulin either from the manufacturing process or from the packaging. Administration of a dose is effected by puncture of a sealing membrane composed of organic and metallic, primarily aluminum, layers. This process may introduce unwanted particulates into the lungs of users and may adversely impact their health over long-term exposures. Regulators require manufacturers to evaluate the presence of such particulates and to demonstrate that they are under control during both the manufacturing and delivery process.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** Current measurements of particulate contamination levels are time consuming and complex and do not support in-line or at-line measurement resuls demonstrating that minimum contamination levels have been attained. As a result, quality control methodologies are inadequate or unavailable. Well-characterized measurement tools are required to quantify the level of contamination. Tools suitable for both R&D and manufacturing environments must be available. The reliability and consistency of the techniques and instrumentation must be well documented and reevaluated on a regular basis. Standards are required to calibrate and perform quality control tests on process measurement and quality assurance tools.

***Potential Solutions to Measurement Problem*:** FDA-acceptable methods for compositional and morphological measurements of micron-scale contamination in pharmaceutical powder formulations; new standards and methods enabling performance evaluation of high-throughput particle analysis systems.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Simulation and Modeling New Materials and New Manufacturing Processes.

***Submitter*:** Dan Friend

***Technological Innovation at Stake*:** Inability to accurately model and simulate the behavior of new products, processes, or materials impedes manufacturing in the automotive, electronics, materials, and chemicals industries.

***Economic Significance of Innovation*:** Lack of safety data for innovative, advanced materials results in extra costs for producers that do not provide qualities that protect consumers. In testimony before the House Committee on Regulatory Reform, the US Chamber of Commerce quoted: "the cost of regulation is estimated at approximately $850 billion annually" and urged full implementation of the Information Quality Act (IQA) to reduce unnecessary economic burdens of regulatory compliance. Better safety data can help make products both cheaper and safer.

***Technical Barrier to the Innovation*:** A major contributor to poor performance of models simulating the behavior of innovative products, processes, or materials is that the Nation lacks a unified, central resource providing and assuring the quality of the data required to support decisions that impact the deployment of new materials and processes in manufacturing. The result is a haphazard collection of incomplete data sets with unknown reliability upon which manufacturing, regulation, and stewardship decisions must be based. For example, several widely used chemical solubility databases have been shown to be incorrect for all the transition metal carbonates and metal sulfides, but continue to be widely used, an issue raised in Congressional testimony. Preliminary information about the risks of new technologies, for example nanotechnology, has been highly sensationalized, yet no effort to systematically collect, assess, and measure the data needed for risk analysis has been authorized.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** There are system level and scientific barriers that must be overcome. System-level barriers involve engagement of industry and regulators in a collaborative effort addressing high priority questions impacting innovation and provision of an infrastructure facilitating the necessary scientific collaboration. The scientific challenge is developing objective, robust, scientifically sound consensus on methods and standards for measuring property data and assuring its quality.

***Potential Solutions to Measurement Problem*:** Provision of an effective IT infrastructure for the collection, curation, and dissemination of all the relevant data can follow models already extant at NIST. The barrier is the requirement of a major investment and a National commitment to collaboration. Objective, robust, scientifically sound methods for measuring data quality can be realized through expert system software realizing conformance with physical and chemical laws and utilizing robust statistical evaluation algorithms.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Advanced Power Cycles for Electric Power Generation

***Submitter*:** Allan H. Harvey

***Technological Innovation at Stake*:** There are several candidate processes for advanced power cycles, i.e., conversion of mechanical energy derived from combustion to electrical power, of improved efficiency with lower emissions. For example, the "oxyfuel" zero-emissions process combines high-temperature, oxygen-fed combustion with CO_2 sequestration. The integrated gasification combined-cycle (IGCC) process uses gas synthesized from coal to replace natural gas to fuel a combustion turbine that subsequently provides the heat source for steam turbines while removing CO_2 from its effluent stream.

***Economic Significance of Innovation*:** In its 2006 Annual Energy Outlook, the Energy Information Administration projects the need for 174 GW (gigawatts) of new coal-fueled generation capacity in the U.S. by 2030; this represents an investment of about $250 billion in new coal plants over the next 25 years. Advanced cycles can provide additional energy capacity with higher efficiencies, over 50% for some cycles, compared to 40% for typical current coal-fired plants, with reduced emissions, and with greater fuel flexibility that can reduce operating costs.

***Technical Barrier to the Innovation*:** These advanced power cycles operate at conditions of pressure, temperature, and most importantly CO_2, H_2, and H_2O composition far different from those for which we have engineering experience and supporting thermophysical property data. The ability to evaluate design alternatives, assess economic feasibility, and optimize the engineering design of proposed plants is severely hampered by the lack of such data for high-temperature water-containing gases involved in the cycles.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Experimental determinations of property data of the requisite accuracy are extremely challenging for the conditions of interest and themselves will require development of innovative thermophysical property experiments. There are as yet no reliable predictive models that enable estimation of system behavior for these water-rich systems under relevant conditions of concentration, temperature, and pressure. As models are developed experimental data over previously uncharted regions will be required for their validation.

***Potential Solutions to Measurement Problem*:** Our ability to computationally predict thermophysical properties from fundamental physical laws is poised to address the systems and conditions of interest for these advanced power cycles. These properties may be determined rigorously if the intermolecular potential function can be calculated with sufficient accuracy. Computational chemistry has advanced to the point where this type of "virtual measurement" is feasible for the molecules of interest here. High-temperature experimental capabilities, covering a subset of the parameter space of interest, must be developed to provide the necessary validation of the theory.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Measurement and Control of Superalloy Contaminants

***Submitter*:** J. R. Sieber

***Technological Innovation at Stake*:** Superalloys are the most reliable, cost effective, high-strength material capable means of coping with high temperature, high stress conditions in advanced aerospace and industrial applications. The performance of superalloys and high temperature alloys in advanced power generation and aviation turbines can be strongly degraded by the presence of contaminating constituents at concentrations below the 10 mg/kg level. Increasingly stringent engineering requirements and environmental regulations drive more rigorous materials certification needs over an increased range of constituents.

***Economic Significance of Innovation*:** Today, 50% by weight of advanced aircraft engine parts are superalloys. They are widely used in land-based, electricity generation turbines, in rocket engines, chemical plants, oil production equipment, biomedical implants, and building construction materials. Equipment failure due to superalloy component failure can have catastrophic consequences both economically and societally.

***Technical Barrier to the Innovation*:** As superalloy demands grow, so does demand for improved compositional analysis technology. The metals industry is facing a significant challenge of certifying superalloy constituent concentrations. Alloy producers must measure more than 20 elements in their products, many at levels that challenge current analytical capabilities. Analytical instrumentation used for certifying content requires calibration by certified reference materials (CRMs). Industry and metrology institutes are faced with the conundrum that CRMs cannot be developed because superalloys are not sufficiently homogeneous, yet industry cannot create more homogeneous superalloys in part because the CRMs are lacking.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** Improved measurement technologies are needed for assessment of micro scale, elemental alloy heterogeneity, and determination of numerous elements, some with highly similar chemistry that complicates the measurement problem. Measurement technologies are becoming available, but at costs too high for industry to acquire and use. Some are so highly specialized that they are only available from a few sources. Increasingly stringent performance goals result in a continuous stream of new alloy compositions. Continual reduction of element concentrations combined with more stringent accuracy specifications requires new measurement methodologies to provide advanced reference materials.

***Potential Solutions to Measurement Problem*:** Collaboration between the metallurgical and analytical communities will yield alloys of sufficient homogeneity to qualify as candidate materials for CRM development. Producers and users must agree on the most pressing needs and establish goals for homogeneity of materials and uncertainty of analytical results. Metrology institutes can verify homogeneity at the micro scale, then work with other CRM providers to create improved CRMs. Improved CRMs provide a basis for SDOs to improve measurement result reliability among producers and users. Continually decreasing concentration requirements drive the need for new measurements capabilities upon which to base CRMs of higher accuracy.

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Case Study – Measurement Needs

***Technology at Issue*:** Nanostructured Materials for Photovoltaic

***Submitter*:** S. Robey, L. Richter

***Technological Innovation at Stake*:** Successful development of nano-structured organic and organic-inorganic hybrid photovoltaic (PV)/solar cell technologies holds great potential for the development of solar energy modules at costs competitive or below current costs of fossil fuel generated electricity. Broad usage of PV technology innovations will reduce dependence on imported natural gas and reduce greenhouse gas and particulate emissions from coal-fired power plants. The architecture of power generation will also change with reduction of large generation sources replaced by a distributed renewable, non-polluting, domestic energy source. Low-cost, reliable, long-lived PV modules will also reduce the strain power distribution grids.

***Economic Significance of Innovation*:** Combustion processes, natural gas and petroleum (~20%) and coal (50%) are the dominate energy producers of electricity generation and of the dominant greenhouse gas, CO_2, emission, ~20 tons yearly per U.S. consumer. U.S. electricity generation with natural gas averaged ~27% of total imports between 2001 and 2005 at costs ranging from ~$20B (2001) to $44B (2005). Technological innovations that reduce U.S. dependency for electricity produced by combustion process costs, both economic and environmental, improve our economic and societal health. Innovation in PV technologies provides a means to reduce U.S. dependence on combustion-generated electricity with significantly reduced environmental issues (air pollution, mining effects, oil spills, etc.) and U.S. reliance on foreign natural gas. New PV technology development and implementation are costs that reduce the economic impact of their use.

***Technical Barrier to the Innovation*:** The principles of operation of revolutionary nano-structured organic and organic-inorganic hybrid PV technologies are fundamentally different from conventional inorganic (Si) solar cells. Processes occurring at interfaces (exiciton dissociation/recombination, charge and energy transport) in nanosstructured material blends (organic-organic, organic-inorganic nanocrystal) dominate operating efficiency. Understanding correlations between interfacial electronic structure and molecular/atomic structure and their interplay charge transport and exciton dissociation processes, and their connection to nanoscale morphology, is crucial to the achieving high efficiency, i.e., cost/Watt, targets that can spur widespread PV use.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Discovery science is needed to better understand physical/chemical mechanisms governing operation of future devices. Measurement methods with spatial and temporal resolution for nanoscale structure, combined with spectroscopic/physical parameter measurement, are are needed to gain insight into charge generation and transport processes in nano-structured materials of interest for advanced PV technologies.

***Potential Solutions to Measurement Problem*:** Non-destructive measurement methods with nanoscale spatial resolution, combined with high speed spectroscopic/physical parameter measurement, suitable for small organic molecule/polymer systems are needed. Atomic force microscopy methods and its variations are lkely to allow measurements under actual illumination, in addition to use of advanced electron microscopies.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Nuclear Magnetic Resonance Spectroscopy Tools for Drug Design

***Submitter*:** J. Marino

***Technological Innovation at Stake*:** Next generation drugs will target structural characteristics of the macromolecules that are a primary agent of human diseases. A basic premise of drug discovery is identification of chemicals that selectively fit into the structure, i.e., binding pockets, of such disease-specific macromolecules. Binding by smaller drug molecules inhibits macromolecular function thereby halting, or mitigating the progress, of a disease. Future therapeutic design requires knowledge of structure, dynamics and interactions of both the macromolecules associated with diseases and the smaller molecules that critical drug components.

***Economic Significance of Innovation*:** Pharmaceutical companies invest billions of dollars annually to design drugs that specifically target disease related to proteins and nucleic acids. Approximately 30% of this investment goes to structural determination. With improved molecular structure information about disease-causing macromolecules, specific drugs can be designed with greater efficacy. This information can be utilized at every stage of the drug discovery process, from target validation to lead optimization. A prominent example of the benefit of structure determination for drug discovery comes from programs initiated to discover HIV-1 protease inhibitors. In these programs, the availability of structural information at a very early stage markedly accelerated the speed at which the first inhibitors were brought market and has subsequently aided in the process of re-design of new drugs to meet the challenge of viral drug resistance.

***Technical Barrier to the Innovation*:** NMR spectroscopy is the most powerful spectroscopic tool currently available for the structure determination of macromolecules based on accurate measurements of a sufficient set of distance, angle and orientation of the atoms comprising a macromolecule. These measurements are enabled by the substitution of NMR-active isotopes that clearly identify specific portions of the molecule of interest. A current technical barrier to full utilization of structural information is an accepted and evaluated set of reference data and standards that would provide a set of general criteria against which researcher could judge the accuracy and precision of solution structure data. Development of standards could allow the development of a general 'confidence level' measure for macromolecular solution structures that would allow strategic planning on if and/or how available data could best be utilized in the drug discovery process.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The comparability of determinations result is significantly impaired by the lack of currently accepted standards for validating the accuracy of an NMR-determined macromolecular structure. Therefore, inaccuracies in the determined structure of macromolecules may exist in the current literature and structural databases with no widely agreed standard tools useful for independent assessment of structural information. These inaccuracies lead to inconsistencies when attempts are made to use the structures for drug design or in research efforts aimed at understanding macromolecular function in disease, leading to added cost in time and money to determine the structural basis for the interaction of drugs with targeted proteins and nucleic acids.

***Potential Solutions to Measurement Problem*:** Development of relevant measurement science supporting standards, and reference data to validate the accuracy of the NMR determined macromolecular structures.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Airborne Contamination in Semiconductor Wafer Processing

***Submitter*:** J. T. Hodges

***Technological Innovation at Stake*:** Manufacturing of future generation semiconductor devices, having smaller physical feature size, higher speed, and lower cost, can be limited by the presence of airborne molecular contamination (AMC). Production yield is expected to be adversely impacted in 300 mm and larger diameter wafers. Numerous process steps in the production of semiconductor wafers utilize ultra-high purity gases, which can contain airborne molecular contamination. In the long-term, AMC concentration specifications required of gas suppliers by IC manufacturers will be below the 1 ppb level. Trace quantities of AMC in process gases also degrade manufacturing yield of integrated photonics devices and custom nanomaterials.

***Economic Significance of Innovation*:** The semiconductor industry now represents nearly 1 % of the US GDP and in terms of value added is the largest manufacturing industry in the US and sustains high-wage jobs. The photonics industry (approximate $20 billion/yr), largely supporting telecom applications, is also a significant and growing sector, which relies on devices fabricated from wafers. A recent study [http://mph-roadmap.mit.edu/about_ctr/report2005/] indicates that for the optical communications industry to prosper, electronics and photonics must merge to generate a new breed of devices that will be manufactured in large volume at low cost to power devices with greater functionality, which increases consumer benefits. Given that a 1 % yield increase corresponds to approximately $1M per day increase in profits for a 300 mm fabrication facility, relatively small improvements in yield associated with improved metrology and process control improve profitability for IC manufacturers.

***Technical Barrier to the Innovation*:** AMC must be controlled by specialty gas suppliers in high purity gases supplied to the semiconductor and photonics industries. Current measurement methods having the required concentration detection capability require expensive and bulky off-line instrumentation to characterize impurities in semiconductor process gases. Consequently, users rely on supplier-specified impurity levels in delivered gases, with no knowledge of the contamination level at the point of use.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** More compact, flexible, in-line and/or in situ measurement systems are needed for high sensitivity contaminant concentration measurement at the point of use for contamination by species such as H_2O, CO, CO_2, CH_4, and NH_3. This is a challenging measurement at concentrations less than 1 parts-per-billion.

***Potential Solutions to Measurement Problem*:** To address this issue, gas purity must be characterized by high accuracy, species-specific measurement techniques that are non-invasive, robust, reliable and able to clearly discriminate signal from contaminants within the process gas. Promising laboratory-level methods must be engineered to provide high-sensitivity process sensors capable of use in manufacturing environments. Diode laser instruments using optical absorption spectroscopy have been shown to provide quantitative gas purity measurements at the required levels, <1 ppb. Species selectivity is required and enabled by narrow bandwidth lasers and the high sensitivity afforded by resonant optical cavities.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Truth-in-Labeling of Dietary Supplements

***Submitter*:** K.E. Sharpless

***Technological Innovation at Stake*:** Manufacturers of dietary supplements sold in the U.S. will soon be required to evaluate the identity, purity, quality, strength, and composition of their ingredients and finished products under the U.S. Food and Drug Administration's (FDA's) proposed rule for good manufacturing practices (GMPs) for dietary supplements. This is a significant departure from current practice and will require an infrastructure of measurements and standards that is largely non-existent. These regulations are driven by reported cases of inaccurate labeling, adulteration, contamination (with pesticides, heavy metals, or toxic botanicals), and drug interactions. The actual concentrations of ingredients, and the presence of contaminants and adulterants, in dietary supplements are typically unknown by consumers, researchers, and manufacturers.

***Economic Significance of Innovation*:** In 2004, consumers in the United States spent more than $20 billion on dietary supplements. Growth is expected to continue at a rate of 3 % to 5% per year. About 75% of the US population takes dietary supplements, including vitamin and mineral supplements, to increase their daily intake and/or for perceived health benefits. The proposed rule for GMPs, which estimates an annual costs/benefit ratio of benefit-cost ratio of 2.5:1 ($218M/yr market), specifies the use of standard reference materials for laboratory control processes. Manufacturers' use of recognized measurement technologies and standards will provide the means for removal of contaminated or adulterated ingredients and products from the marketplace, improve public health and safety, provide consumers more accurate labeling information, and increase public confidence in supplement consumption. Public health agencies will have a quantitative basis for conclusions about use of individual dietary supplements.

***Technical Barrier to the Innovation*:** A comprehensive measurement system, including analytical methods and reference materials for the analysis of dietary supplements is largely non-existent. Although some protocols for individual testing laboratories exist, e.g., NSF/ANSI 173 – Dietary Supplements (2005) and AOAC's Single-Lab Validation protocol, the means for demonstrating the accuracy of measurement methods for dietary supplements are largely unavailable.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** Measurement methods that provide manufacturers with content information on the raw materials used to make supplements and throughout the production process are largely non-existent. Measurement methods and certified reference materials (CRMs) are needed to support quality control and compliance with the FDA's proposed GMPs for supplements.

***Potential Solutions to Measurement Problem*:** Develop analytical methods for measurement of ingredients and contaminants in dietary supplements and produce CRMs for use in quality assurance. Broad recognition and acceptance of new analytical methods and the supporting reference materials will ease transition to more accurate labeling and GMP compliance.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Advanced DNA Analysis Using Lab-on-a-Chip Technology

***Submitter*:** B. Jones

***Technological Innovation at Stake*:** DNA analysis genome analysis for forensic, healthcare, agricultural and environmental applications using ultra-small sample size. Lab-on-a-chip technology promises rapid and inexpensive approaches to DNA analysis for the many applications where genomic information provides insights into the state of biological systems. This new measurement technology has the potential to offer many advantage, low fluid volume consumption reduces waste, lower cost accrue because only small amounts of expensive reagents are needed, and higher analysis and control speed results due to short mixing times, fast heating times coupled with small heat capacity significantly reduced power consumption thereby enabling single use approaches at much reduced cost. Lower fabrication costs of mass production promise a safer platform for chemical, radioactive or biological studies because of large integration of functionality and low stored fluid volumes and energies.

***Economic Significance of Innovation*:** DNA analysis technology has permeated many sectors of the economy including agriculture, industrial processes, environmental biotechnology, and healthcare and forensics. Future applications in healthcare include genetic targeting of pharmaceutical production and diagnostics, and the individualization of drugs and other therapies. The agricultural sector has a great need for a cost effective means of testing exports for genetic modification, while environmental biotechnology employs DNA analysis in the bioremediation of sites contaminated with organic waste. Lab-on-a-chip DNA analysis technology greatly reduces the cost of the analysis device, in many cases from hundreds of dollars to pennies, decreases the time of each analysis from many hours to mere seconds, and considerably reduces the capital expenditure for analytical instruments, and facilitates automation.

***Technical Barrier to the Innovation*:** Lab-on-a-chip DNA analysis requires miniaturization of analytical components such as thermoregulation for polymerase chain reaction (PCR) replication of DNA, separation of DNA fragments, and optical or chemical detection. Multiplexing of these analysis components requires complicated interfacing and device fabrication.

***Stage of Innovation Where Barrier Appears*:** R&D, Production

***Measurement-Problem Part of Technical Barrier*:** Industry's need to characterize 3-dimensional features of a microdevice as well as materials characterization in a high throughput format is universal. Specific to microfluidic devices is the need to accurately measure flow, viscosity, electrophoretic mobility, temperature, fouling, and fluorescence calibration within a microchannel.

***Potential Solutions to Measurement Problem*:** New technological approaches are needed. Academic, private sector and government laboratories have active R&D efforts. NIST can provide standard methods to accurately measure parameters such as flow, temperature, channel dimensions, and electrophoretic mobility among others is critical to bring micro-analytical processes into control.

Case Study – Measurement Needs

***Technology at Issue*:** Cell Based Analysis using Lab-on-a-Chip Technologies

***Submitter*:** B. Jones, L. Locascio

***Technological Innovation at Stake*:** Robust and reproducible methods are needed to determine the response of biological cells to proposed compounds in pharmaceutical development and approval. The at-cell analysis capability afforded by combination of chemical analysis methods with microfluidic device technologies, Lab-on-a-Chip, may allow multiplexed delivery of toxicological agents/cell insults with immediate diagnostic quantification of metabolic responses, a capability currently unavailable. This cell-based analysis will decrease analysis time, eliminate the need for large samples, and enable toxicological analysis of different cell types (liver, lung, heart) in one assay. Additionally, this format enables ultra-low concentration detection of harmful metabolites dangerous in later animal and human trials.

***Economic Significance of Innovation*:** It is estimated that only one out of 10,000 drug candidates ever reach the consumer. Each drug costs over $897 million to take from conception to FDA post-approval. This R&D cost plays a major role in limiting pharmaceutical development. Current estimates for costs due to poor absorption, distribution, metabolism, elimination or toxicity (ADME/Tox) properties alone are $50-70 million annually. Each year the Pharmaceutical Industry generates $550 billion in revenue worldwide. The potential impact to this industry in improving the ratio of drugs taken from conception to market and reducing ADME/Tox problems early in the screening process could result in billions of dollars in economic gains and potential health with significant associated societal benefits.

***Technical Barrier to the Innovation*:** The maturity of this technology is dependent on cell viability within microchannel devices. In addition, materials and device physical characterization is important as well as standardization of microfluidic processes in order to fully control analysis progression.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Measurement and standardization of cell viability within the micro-environment is essential. Measurements of the microfluidic parameters such as flow temperature, viscosity, fluorescence calibration, and device fouling; and on-chip measurements of complex biology-surface interactions, nutrient delivery, cell manipulation, and electrophoretic mobility are also vital to device development.

***Potential Solutions to Measurement Problem*:** Bottom-up solution development, i.e., proceeding from fundamentals of biology and chemistry, is necessary because modification of existing methods is not a reasonable expectation. Standard methods to accurately measure parameters such as flow, temperature, channel dimensions, and electrophoretic mobility among others is critical to bring micro-analytical processes into control.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Nanoscale Chemical Characterization of Advanced Materials

***Submitter*:** Stephan Stranick

***Technological Innovation at Stake*:** A broad range of future generation products and processes will be founded on reliable manipulation and tuning of material properties to take advantage of novel physical and chemical properties only available through use of nanoscale phenomena. Discovery of the mechanisms controlling these phenomena rely heavily upon nanoscale chemical characterization and chemical imaging. Real time, non-destructive, chemically specific visualization of nano-scale components and materials is critical to the development of these. Non-destructive, real-time, 3-D chemical imaging with nanoscale resolution will enhance progress in understanding nanoscale systems and will be a critical measurement capability necessary for the advance of nanoscale-based products.

***Economic Significance of Innovation*:** Through advances in nanoscale chemical imaging, the U.S. will increase our basic understanding to implement "tuning" of advanced material's properties. An example of this found in the automotive industry is a class of engineered plastics, thermoplastic olefins, widely used in automotive fascia and bumpers. The US market for these materials in 2005 was $2.4 Billion and growing at a rate of almost 6% annually. Optimizing this growth requires detailed nanoscale chemical information, so that manufacturers can tailor formulations to minimize expensive components, to the extent possible, without compromising performance. Here, high directional strength is often an important driver that make the new material's technologies more affordable, durable or environmentally friendly at good value. Ultimately, the resulting value creation and cost savings associated with optimization of thermoplastic products through advanced capability in nanoscale chemical imaging diagnostics is estimated to be in the 10- 20% range annually.

***Technical Barrier to the Innovation*:** Descriptions of nano-scale phenomena that allow engineering of materials properties are lacking. The success of investigations of the mechanisms controlling such systems are based on observation of material behavior, often in real-time and under conditions of use. Currently available chemical imaging techniques lack sufficient spatial resolution, chemical identification resolution, and/or the ability to probe into the bulk of the material so that observed behaviors attributed to bulk phenomena are not the result of interfacial behavior that may be very different.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Currently most imaging of nanoscale objects is accomplished with either scanned probed microscopies or electron and ion microscopies. Electron and ion methods are primarily performed in vacuum environments and can depth profile samples to obtain chemical identification and quantification information using destructive methods, while scanned probe methods are strictly limited to surfaces. Non-destructive imaging techniques are needed that are applicable to a range of materials with nanoscale spatial resolution, sub-surface imaging capability, and the ability to distinguish both between chemically similar and dissimilar materials.

***Potential Solutions to Measurement Problem*:** Linear and non-linear optical methods that couple chemically specific spectroscopies (infrared absorption and Raman) with advances in super-resolving optical elements (adaptive optics) to provide nanoscale chemical analysis. These photon based techniques would overcome the restrictions presently placed on electron and ion based chemical imaging techniques mentioned above.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Nanoscale biological imaging

***Submitter*:** S. Buntin

***Technological Innovation at Stake*:** Successful development of complex biological systems at nanometer dimensions will be limited without the capability to make quantitative determination of the composition of the individual atoms and molecules comprising them. A quantitative understanding of the distribution of chemical species in three dimensions including the internal structure, interfaces and surfaces of micro- and nanoscale systems are critical to the development of successful commercial products in nanotechnology. Current nanoscale-chemical 3D measurement tools are in their infancy. The aggressive development of diverse measurement technologies will overcome critical measurement barriers significantly promoting the a wide range of nanoscale technologies.

***Economic Significance of Innovation*:** Biotechnology is a critical sector for the U.S economy, as the source of innovative firms, high-wage jobs, and products with a high value in both financial and human health terms. Potential applications of a nanoscale-chemical 3D measurement tools in bioprocessing and biotechnology include improved drug delivery systems, more effective clinical diagnostics, and increased biomedical knowledge. Even small improvements in research, manufacturing or clinical efficiency would yield substantial economic gains and provide improved diagnosis and treatment of human disease.

***Technical Barrier to the Innovation*:** There have been remarkable advances in the development of bioimaging techniques over the last few decades. Medical diagnostic imaging tools such as Computer Aided Tomography (CAT), Magnetic Resonance Imaging (MRI) and Positron Emission Tomography (PET) have revolutionized the diagnoses and treatment of disease. New developments in drug discovery, clinical diagnostics and nanotechnology are driving a push for development of novel measurement approaches that will extend bioimaging to the cellular and even molecular level. Current state-of-the-art approaches typically utilize fluorescent optical microscopy but suffer from limited spatial resolution and the inability to provide compositional analysis. New imaging technologies based on electron, ion and photon beam probes must be developed to push biomedical imaging to the nanoscale level. While potentially promising, these techniques are currently of limited use for the nondestructive/noninvasive imaging of processes within living cells and tissue where length scales of interest are commonly a few nanometers.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The combination of high spatial resolution to provide sufficient 3-D information necessary to develop new nano-molecular technologies. There are no existing measurement techniques that combine high spatial resolution with chemical compositionally specific non-invasive, nondestructive in-vivo real-time imaging. Trade-offs are made whenever ion, photon, or electron methods are selected, leading to extra work, greater expense, higher uncertainties and incomplete specimen characterization.

***Potential Solutions to Measurement Problem*:** Substantial improvement in optics for optical microscopy (thus keeping the real-time living specimen capability but improving resolution), or improvement in electron and ion techniques for atmospheric pressure measurements would create substantially more efficient and informative bioimaging techniques. Development of nanoscale biomarkers useful with current technologies also offers significant potential.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Quantity Determination of Hydrogen for Fuel Cell-Based Vehicles

***Submitter*:** John Wright

***Technological Innovation at Stake*:** The use of hydrogen as a fuel for energy production in transportation and for residential use will require a production, storage, and distribution infrastructure that qualitatively differs from that supporting today's infrastructure. Establishing an orderly market supporting the equitable commercial exchange of hydrogen fuels will require a range of new technologies, measurement technologies being a central one, for supporting fair and equitable exchange of hydrogen as a fuel.

***Economic Significance of Innovation*:** At a price of $60 per barrel of crude oil, the US spends approximately $300 billion on oil for transportation purposes each year. Replacing internal combustion engines in vehicles with fuel cells replaces one cost, IC engines, with another, fuel cells, however, elimination of pollutants associated with IC engines has potential to dramatically alter adverse environmental impact, if a similarly non-polluting source of energy can be used to produce the hydrogen subsequently used in hydrogen fuel cells for both transportation, residential, and light industrial usage. However, the cost of converting and extending the current distribution infrastructure for gasoline and natural gas will involve significant capital expenditures.

Technical Barrier to Innovation: Hydrogen fuel distribution systems suitable for broad public usage must be developed. Partial utilization of current pipeline transportation systems provides a base from which to start. Quantification of hydrogen passing through such systems will be required for custody transfer purposes for both wholesale and retail distribution. Safe handling procedures and new materials performance requirements are necessary to deal with long-term exposure, high pressure containment requirements. Quantification methods that adequately deal with the large difference in behavior and properties of hydrogen relative to those of other gases currently widely distributed will be needed. Adaptation of codes governing accurate billing at fuel pumps must be made and accepted by both the user, supplier, and regulator communities.

***Stage of Innovation Where Barrier Appears*:** R&D and End Use

***Measurement-Problem Part of Technical Barrier*:** Present prototype hydrogen re-fueling stations for retail purposes use flow meters to totalize hydrogen flow at the dispenser that are require improved performance characteristics. However, there are no standards that can monitor the performance of such meters during transients. Versatile, transient-tolerant, low-uncertainty, flow measurement standards are needed for performance evaluation candidate hydrogen metering technologies. Standards and procedures analogous to those currently used to regulate fueling station performance must be developed and implemented.

***Potential Solutions to Measurement Problem*:** Establish flow measurement standards for delivering hydrogen, including effects due to flow transients. The physical properties of hydrogen and hydrogen-rich fuels are needed at higher levels of accuracy than are currently available. Develop test methods for evaluating performance of flow metering technologies that will be developed specifically for hydrogen. Regulatory procedures and standards are needed that provide state agencies with capabilities analogous to those they currently use to regulate the sale of motor fuels.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** High Accuracy Metering for Natural Gas Transportation Pipelines

***Submitter*:** John Wright

***Technological Innovation at Stake*:** Improved quantification of natural gas in high pressure, large diameter distribution pipelines requires improved measurement of flow rate and gas density measurements. Improvements in natural gas quantity determination by approximately a factor of 10 will improve confidence in the equitable importation and distribution in the U.S. In the next decade, natural gas imports will increase as domestic demand rises and domestic production is reduced. Improved in-line quantification of natural gas are needed to ensure equity in trade in the international natural gas market.

***Economic Significance of Innovation*:** In 2004, the US imported $21 B of natural gas from Canada through pipelines and approximately $4 billion of liquefied natural gas from other countries. With 3% of the world's reserves, the U.S. will increase natural gas imports. Approximately 2/3 of the electrical generating capacity planned to become available by 2009 is anticipated to be natural gas fired. Current U.S. natural gas usage exceeds $100 B/yr. It is the fuel of choice due to its clean burning characteristics, low particulate emission, for industries, e.g., chemical, petrochemical, and materials processing, requiring large heat sources. Typically custody of natural gas shipments/transfer occurs 5 to 7 times from source to consumer. Measurement accuracies are approximately 0.5%, which translates into variability in transfer costs exceeding $1 B/yr. These costs are incurred by businesses. A factor of 10 in quantity determination accuracy will reduce this amount significantly. Additionally, access to global markets for US instrumentation manufacturers depends upon international acceptance of pertinent standards and measurements protocols.

***Technical Barrier to the Innovation*:** Improved performance levels substantiated by nationally and internationally measurement standards are required to both evaluate the accuracy capabilities of new technology developments. International recognition is required for legal metrology usage in foreign countries.

***Stage of Innovation Where Barrier Appears*:** Marketplace

***Measurement-Problem Part of Technical Barrier*:** New approaches are needed that improve US flow standards of metering devices used in high pressure, large diameter, natural gas pipeline services to both support future importation to the US and to support export of such technologies to other countries. National metrology institutes in Germany and the Netherlands claim to calibrate pipeline-scale flow meters with an uncertainty of 0.16%. No US entity can achieve this low uncertainty. Flow meter calibrations in the U.S. is provided by the Southwest Research Institute, SwRI, and the Colorado Engineering Experiment Station Inc., CEESI, at approximately the 0.3% level, and are not accepted by the EU and gas producing countries. Improved US standards and measurement technologies will give greater confidence in import quantification and overcome this technical barrier to international trade.

***Potential Solutions to Measurement Problem*:** Establish partnerships between NIST and existing US commercial calibration laboratories, CEESI and SwRI, to improve standards capabilities for natural gas flows in these regimes. NIST can provide expertise in quality systems, uncertainty analysis, traceability, new measurement techniques, and international comparisons among flow standards. CEESI and SwRI can provide facilities and metering expertise.

***Technology at Issue*:** Nano-Scale Drug Delivery

***Submitter*:** S. Buntin

***Technological Innovation at Stake*:** Nanoscale drug delivery systems and formulations engineered to provide more potent and targeted doses through higher bioavailability, ultimately affording highly effective treatments with fewer adverse side effects.

***Economic Significance of Innovation*:** In the year 2000, the share of the U.S. GNP attributed to healthcare costs was about 13%, and forecast to rise to about 16% in the year 2005. The fraction of total healthcare cost in 2000 devoted to drug expenditures was estimated at about 10%, with the market size for drugs and drug delivery systems projected to grow from an estimated $47 billion in 2002 to $67 billion in 2006. Research is now focusing on innovative nano-particle systems to achieve higher dose efficiencies and potencies, thereby reducing drug expenditures in the future while simultaneously providing for improved health outcomes.

***Technical Barrier to the Innovation*:** Nanoparticle drug formulations, use of drug particles 1/100 the size of a red blood cell, can circumvent side effects and allowing for the facile transport into cells. For example, a 20 fold improvement was observed over conventional formulations for nanoparticle ampicillin in eradication of Listeria. Abraxane (American BioSciences, Inc), an albumin-bound nanoparticle anti-tumor agent, is much more effective in breast cancer treatment than conventional formulations, without solvent-induced side effects. For continued to development of such innovative drug formulations, new tools are needed to determine and assure quality and reproducibly. Control of particle size, composition and morphology for both organic-based pharmaceutical nano-particles and organic-inorganic hybrid nanostructures must be achieved for these new delivery systems. Further, the increasing design complexity of drug delivery formulations, comprising multiply layered polymeric biomaterials, exacerbates this challenge. Nanoparticle formulations typically allow drugs to have much higher potencies than conventional formulations by increasing availability of active agent in the blood stream. Most drugs have very low solubilities, severely limit their effectiveness and potency.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** Particle measurement instruments currently available to the pharmaceutical industry lack the spatial resolution and compositional and morphological characterization sensitivity necessary to advance both discovery efforts and production of drug delivery devices employing nanoscale components. New or improved methods are needed for surface, near-surface (1-100 nm), and full 3D nanoscale characterization for drug development and in-line diagnostics for methods validation and quality assurance/control of manufacturing processes.

***Potential Solutions to Measurement Problem*:** New technologies, such as advanced mass spectrometric methods, sub-diffraction limited optical techniques and electron microscopies must be developed. These will then be the basis for protocols that include reference materials, calibration standards, and reference data supporting in-line manufacturing process monitoring for compositional and morphological characteristics critical to drug product efficacy that are needed to support clinical trials of nanoscale drug delivery systems, and ultimately widespread usage.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Carbon Nanotubes (CNTs)

***Submitter*:** Ian M. Anderson

***Technological Innovation at Stake*:** Improvement of a wide variety of products through judicious substitution for conventional materials of CNTs, which exhibit unique properties: "the strongest fiber that will ever be made; electrical conductivity of copper or silicon; thermal conductivity of diamond; the chemistry of carbon; the size and perfection of DNA".

***Economic Significance of Innovation*:** CNTs have the potential to improve a host of composite materials across numerous economic sectors. Potential applications of CNTs range from reinforcing fibers for car bumpers to cathodes for flat panel displays, from storage materials for hydrogen fuel to conductive inks for rear-window defoggers.

***Technical Barrier to the Innovation*:** CNTs are not synthesized or supplied in pure form, but as a mixture of various CNTs, other carbonaceous species, and noncarbonaceous species. Suppliers of CNTs regularly adjust their synthesis routes to improve key specifications such as production rate, purity, length, and degree of aggregation. However, these supplier adjustments may alter the CNT batch properties, making them unsuitable for a target application of a given manufacturer.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** Currently, there is an absence of robust methods to characterize the distribution of species within a batch of CNTs. Manufacturers regularly qualify batches of various raw materials in their quality assurance (QA) laboratories, but protocols for the qualification of CNTs have yet to be devised. Ideally, a suite of measurements would be devised to quantify: the mass fractions of CNTs, other carbonaceous species, and noncarbonaceous species within a batch; the distribution of CNTs according to "chirality" (a characteristic unique to CNTs), the proportion of single-walled (SW) and various multi-walled (MW) tubes, and length; the levels and nature of defects within the CNTs; and the degree of aggregation. Specimen preparation protocols are also required to ensure that QA reproducibility is not compromised by improper handling. Specialized measurements should be available with rapid turn-around through dedicated government or commercial characterization laboratories.

***Potential Solutions to Measurement Problem*:** Specimen preparation protocols that mitigate damage of CNTs for QA measurements; reference materials (RMs) that quantify the characteristics of a batch of CNTs; measurement protocols that correlate these characteristics with quantifiable parameters, preferably obtained with equipment available within a manufacturer's multipurpose QA lab.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Analytical Metrology and Standards for Achieving a Hydrogen Economy

***Submitter*:** G. Downing

***Technological Innovation at Stake*:** The U.S. is striving for a hydrogen-based economy. To achieve the goal, break-through innovations over a range of products and processes is essential. These range from cost-effective fuel production to advanced power sources in a range of end-user appliances. Critical to each phase are rapid and accurate analytical metrics and performance standards. Without the appropriate metrology and metrics, implementing cost-effective technology becomes protracted and industrial-government-consumer interactions become problematic.

***Economic Significance of Innovation*:** Advances ranging from robust, high-efficiency fuel-cell membranes to methods that significantly reduce or eliminate the embrittlement of steel used in pressure containment structures for handling and storing hydrogen are necessary for the utilization of hydrogen as an energy source in the U.S. economy. This will help reduce dependency on over-seas based petroleum, reduces pollution, and advance U.S. technological competitiveness. As an example, currently the U.S. consumes approximately 44 million gallons of gasoline/day, a daily cost over $100 M, primarily in transportation cost. Small incremental savings in these and related energy costs are significant, as is the significant reduction of greenhouse gas, CO_2, emission.

***Technical Barrier to the Innovation*:** Hydrogen fuel cells are a primary technology for conversion of hydrogen to electrical power. Improved understanding of the operation of the proton exchange membranes central to their operation must be achieved if this technology is to succeed economically. Similarly enhanced understanding of the processes that lower the effective strengths of steels used in pipelines and pressure containment vessels are needed as a basis for design of successful alternatives critical to the safe processing and distribution of hydrogen or hydrogen rich hydrocarbons across the U.S. economy.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Chemical analysis methodologies and standards to establish quality control and assurance are entirely lacking in this area. Developing advanced measurement technologies and methodologies for determination of small concentrations of hydrogen in a wide range of materials will be a significant enabling force in R&D.

***Potential Solutions to Measurement Problem*:** Create chemical analysis methods and standards for quantitative measurements of 1) impurities in hydrogen gas and its catalysts, 2) hydrogen embrittlement in pipelines and other vulnerable components, 3) impurities in fuel cells, especially membranes and catalysts, 4) chemical composition and impurities in hydrogen storage materials, and 5) environmental impact.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Measurement Standards Supporting In Vitro Diagnostic Device (IVDDs) Usage

***Submitter*:** Michael Welch

***Technological Innovation at Stake*:** Approximately 60% of IVDDs sold in Europe are manufactured in the U.S. In recent years, the EU has required that the results of measurements made by these devices be traceable to reference measurement procedures and/or reference materials of a higher order. "Higher order" measurement procedures are generally more accurate and specific than the techniques used by IVDDs, typically immunoassays, but are cost-prohibitive for routine measurements. Higher order measurement procedures are used to characterize a reference material used to calibrate and/or evaluate the performance of an IVDD. The results of measurements using IVDDs affect decisions concerning medical treatment, the efficacy of treatment, and appropriate dosages of medications.

***Economic Significance of Innovation*:** The United States is the leading manufacturer of IVDDs, accounting for $10.4 B of the total worldwide market of $26 B in 2003. Approximately 40%, $4 B annually, of U.S.-made IVDDs are exported abroad, with Japan, Canada, and the European Union as the largest foreign markets. Higher-order traceability requirements could present a technical barrier to global trade in these devices. Approximately 15% of the $1 trillion yearly healthcare costs in the U.S. are associated with measurements, with approximately 25% of those constituting repeat measurements due to lack of confidence in the initial results; development of methods that increase confidence in the results of IVDDs can have a significant impact in reducing U.S. healthcare costs.

***Technical Barrier to the Innovation*:** Currently, neither reference materials nor reference methods considered to be of the "highest order" are available for more than 300 different chemical and biochemical species that are measured in medical laboratories using IVDDs. Worldwide, reference methods and/or materials exist for only approximately 30 species. Both reference methods, and the reference materials that result from their use, are needed to support existing and anticipated IVDDs.

***Stage of Innovation Where Barrier Appears*:** Marketplace

***Measurement-Problem Part of Technical Barrier*:** A significant number of barriers inhibit the development of reference methods and materials of the required accuracy. Measurement problems include determination of: the best molecular marker to measure for a given condition; whether the measurement system is sensitive to a single or several forms of marker and the relative sensitivity to each; and whether the results are sufficiently accurate for proper diagnosis and treatment. Confounding issues include: insufficient understanding of diseases at the molecular level; inability to discriminate health markers from structurally similar molecules; difficulty coping with the complexity of blood matrices; sample quantity limitations; and knowledge of how well a system is performing versus the actual value.

***Potential Solutions to Measurement Problem*:** Development of reliable reference methods and certified reference materials and coupling those with both disease markers.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Cell-Based Measurements

***Submitter*:** John Elliott, Anne Plant

***Technological Innovation at Stake*:** The health care industry is increasingly reliant on cells and cell-based assays as the basis of medical therapy, to provide diagnostics information, and for screening of new drug candidates.

***Economic Significance of Innovation*:** 92% of new drugs fail in clinical trials. This failure rate significantly contributes to the high cost of developing new drugs, currently estimated at approximately $1 billion/drug. Cell-based screening, which provides a means to evaluate complex living systems, can result in more biologically relevant responses. This in turn helps reduce the time and cost of drug development, increase the success of clinical trials, and can provide better therapies to patients sooner.

***Technical Barrier to the Innovation*:** The lack of quantitative methods and industry-wide accepted assays and analytical protocols impedes the interoperability of data and the development of cell-based knowledge. Experiments which are not validated, and data are not interoperable at an experimental or data format level, cannot be combined into databases. The lack of quantitative methods for characterization of product is a barrier to QA/QC at the R&D level and a barrier to regulatory compliance

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Accepted experimental and statistical methods for quantifying heterogeneity within a population of cells need to be developed. Sensitive analytical and statistical methods are needed that allow valid detection of a low-occurrence phenotype. An absence of standards for calibrating fluorescence microscopes makes it difficult to compare data from day to day and instrument to instrument. Reference materials for predicted cell response, validated experimental protocols and standard images for validating image analysis protocols are needed. The lack of standards for data formats, metadata formats, and standard formats for exchange between platforms are impeding interoperability of data.

***Potential Solutions to Measurement Problem*:** To map intracellular signaling pathways and provide predictive knowledge of cell response, evaluated quantitative data from cells need to be organized in extensive databases. Reference materials for calibrating fluorescence microscopes, standards for image data format, standards for metadata format, reference materials for controlling cell environment, validated quantitative assays, statistical analysis and standard operating procedures for handling inherent variation in cell populations are critical areas of research.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Cryogenic refrigeration

***Submitter*:** R. Radebaugh

***Technological Innovation at Stake*:** Higher efficiency cryogenic refrigeration as an enabling technology for superconducting electronics, low noise photodetectors, superconducting power systems, cryopumps, gas liquefaction systems, astrophysics research, and space exploration.

***Economic Significance of Innovation*:** Products that can only be operated at very low, cryogenic, temperatures require the use of refrigeration methods that comprise a market currently exceeding $20 B annually. Examples of some existing products using superconductivity are MRI systems, NMR spectrometers for protein structures, cellular phone base stations, and electric power transmission lines. Many other applications could develop if more efficient and compact cryogenic refrigerators were technologically feasible and commercially available. These include improved efficiency in the liquefaction of natural gas, air and hydrogen, valued at >$100 B annually, would reduce refrigeration costs substantially, estimated to be $5 B/yr.

***Technical Barrier to the Innovation*:** Increasing efficiency of cryogenic refrigeration usually requires the identification of individual losses and comparison with models. Measuring and identify such losses in regenerative refrigeration systems (those with oscillating pressures and flows) is particularly difficult because techniques for measuring high frequency oscillating variables and separating various losses have not been well developed. Specialized measurement facilities are required to carry out such measurements.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Heat loss determination in regenerative refrigerators at cryogenic temperatures requires the development of specialized facilities and development of exacting measurement procedures at cryogenic temperatures. Measurement of oscillating pressure, flow, and temperature at frequencies up to about 60 Hz as well as that of acoustic power flow and heat flow are needed. These measurements are challenging to make and currently require sophisticated instruments and measurement procedures not currently available to manufacturers of cryogenic refrigerators.

***Potential Solutions to Measurement Problem*:** Develop specialized apparatus for measurement of losses in cryogenic refrigerators during realistic operating conditions. Use results to improve and calibrate models that can be used by anyone to improve efficiency of manufactured cryogenic refrigerators. Also develop a set of simplified measurement procedures, which are calibrated in the laboratory, that manufactures can perform with minimal instrumentation to determine approximate values of various losses within a refrigeration system.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Advanced Manufacturing Processes Simulation for the Chemical Process Industries

***Submitter*:** Michael Frenkel

***Technological Innovation at Stake*:** Reliable and robust simulation and modeling of new or enhanced chemical processes critical to new product development in the chemical, petrochemical, and related process industries require technical information for all materials concerned in a particular process. Computer-aided design and simulation are widely used to develop more efficient manufacturing processes and new materials over a broad range of industries, including the automotive, energy, and materials sectors of the economy. Critical to the future success of simulation of advanced manufacturing processes is the availability of accurate data, both thermochemical and thermophysical data, describing the chemical and physical fundamentals for reactants and products resulting form manufacturing processes.

***Economic Significance of Innovation*:** Economic competitiveness and sustainability are enormous challenges facing these vital US industries whose combined economic impact approaches $750 B. Even small improvements at the margin have large economic consequences, in terms of maintaining technical leadership, preserving high-wage jobs, and enabling a wide range of other industries. Moreover, this technology creates significant non-financial benefits as well, such as improved natural resource use and improved environmental performance. Significant innovative breakthroughs can result in significant economic advantage.

***Technical Barrier to the Innovation*:** There is a major knowledge gap facing industry, which is rooted in the difficulty to establish physical and chemical data availability, reliability, and the inferences that can be made from our current knowledge base relative to the information needed for discovery and innovation. Innovation in process development is often critically dependent on physical and chemical information. Acquisition of the reliable data is often the route to new products and processes. Knowledge enables innovation, not only by guiding discovery, but also by reducing investment risk.

***Stage of Innovation Where Barrier Appears*:** R&D, Production

***Measurement-Problem Part of Technical Barrier*:** The accuracy of thermochemical and thermophysical data is the basis for reliable chemical process simulation. Although widely published in the scientific literature, such data is not always comprehensive and reliable and must be evaluated for accuracy and consistency with the laws of physics and chemistry for effective use in simulating manufacturing processes. Expert systems are needed that will reliably estimate the limits of physical and chemical property knowledge and support development of strategic property data planning of sufficient scope supporting both experimental measurements and computationally-based estimation.

***Potential Solutions to Measurement Problem*:** Establish and support comprehensive data evaluation and dissemination by a widely recognized and respected organization. Develop algorithms that support strategic measurement planning focused on increasing reliability of existing data and determination of validated predictive techniques broadly applicable to a variety of chemical classes. Collaborative forums including industry, academia, and interested government agencies will enhance the long-term sustainability of such an effort.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Toxicology of Nano-particles in Biological Systems.

***Submitter*:** A. Fahey, NIST

***Technological Innovation at Stake*:** Product innovations that use nanoparticles is rapidly expanding in many sectors of the world economy with their incorporation into a wide range of products including cosmetics, pharmaceuticals, polymer composites, clothing, and microelectronics. Despite the potential gains from nanoparticle-based products, there is concern by many communities about their toxicity. The unique and diverse physico-chemical properties of nanoscale materials suggest that toxicological properties may differ from materials of same or similar composition but larger size. For example, nanoparticles may readily migrate through normal barrier tissues such as skin, enter into the blood stream and from there penetrate internal barrier tissues entering into organs like the brain.

***Economic Significance of Innovation*:** Between 1997 and 2003, worldwide government investment in nanotechnology rose from $432 million a year to just under $3 billion a year. Discoveries made in nanoscience and nanotechnology are expected to be a major driver of the world economy in the next decade. In a report entitled "The Next Small Thing," published in September 2001, Merrill Lynch quotes statistics that project the nano-structured materials market alone to be worth at least $5 billion/year and perhaps as much as $20 billion/year. However, despite the economic impact nanotechnology can yield through its novel properties, lack of sound toxicology of nanoscale structures in humans and animals has the potential to derail the acceptance of nano-structured materials in the marketplace.

***Technical Barrier to the Innovation*:** Effective and accepted methods to assess nanoparticle toxicity do not exist. Evidence demonstrating the migration of nanoparticles through barrier tissues in mammals has only recently been shown. New measurement methods are needed for both clinical effects of nano-structure incorporation in tissues and for characterization of nano-structures through out their life, i.e., before incorporation in tissues as well as following incorporation. It is expected that once incorporated in living tissues, nano-structures will change. Methods having the capability to determine such changes in-situ will greatly aid the understanding the evolution of nanostructures in the body.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Development of usable dose metrics for nanoparticle toxicity is not possible without accurate methods to characterize nanoparticle properties such as composition, dimensional metrology, surface area, shape and structure. In addition the development of dose metrics will also depend on the ultimate fate of nanoparticles in biological tissues. Measurement methods sensitive to both the physical and chemical structure and properties of nano-structures are needed as a basis for assessing toxicological impact of nanoparticle materials in tissues.

***Potential Solutions to Measurement Problem*:** Develop a set of metrics that accurately characterize the toxicology of nanoscale materials. Develop methods to characterize nanoscale materials contained within biological tissues. Develop new measurement approaches for in-vivo and in-vitro of the properties of nano-structured particles and devices.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Identification of Biotechnology-Derived Crops

***Submitter*:** Marcia Holden

***Technological Innovation at Stake*:** U.S. agricultural products companies have developed insect-resistant and herbicide-tolerant varieties of maize, soy and cotton developed through genetic engineering, and in 2005 U.S. farmers planted 123 million acres of these crops. The EU, China, Japan, and other U.S. trading partners have put labeling requirements in place that can exclude biotech crops in these markets. Companies register and obtain approval for the genetic modifications used with importing countries. Importation of registered crops is allowed with no labeling requirement while those crops, and products made from them, with content above the threshold must be labeled. Variation is test results at ports of entry of importing countries can have adverse economic effects on U.S. producers.

***Economic Significance of Innovation*:** Agricultural products are a large part of the US economy and export market. Exports of biotech crop containing food and grain shipments are subject to approval and labeling regulations of importing countries. Failure to satisfy these regulations will result in rejection of shipments. In the case of grain exports, whole shipments, e.g., 4000-ton capacity, have been rejected because differences in test results between the producing and importing countries.

***Technical Barrier to the Innovation*:** Technical barriers, largely measurement and infrastructure issues, exist alongside political barriers. Importation barriers often take the form of minimum allowable quantities, typically <2%, of biotech crops obtained from shipment samples. Although dual infrastructure for commodity crops requires separate storage and transport facilities, mixing of grain from many sources occurs and drives the need for determination of biotech crop composition of individual shipments. Inconsistency of measurement results at various points between the farmer, the exporter and the final consumer have sufficient levels of variation to fuel marketplace confusion. Measurement systems having higher reliability are needed.

***Stage of Innovation Where Barrier Appears*:** Marketplace

***Measurement-Problem Part of Technical Barrier*:** Robust testing protocols require requires (1) knowledge of the genetic sequence of the DNA inserted in the genome, generally a few thousand base pairs, comprised of many millions of base pairs and (2) the ability to detect that sequence with sufficient sensitivity and accuracy. Quantitation is most important when little of the biotech crop material is present. Current labeling regulations apply currently the trace detection level for existing measurement capability. Sensitive gene amplification techniques, qualitative and quantitative PCR, are the methods of choice, need improvement, e.g., methods that are not prone to artifacts.

***Potential Solutions to Measurement Problem*:** 1) International harmonization agreements on the use and development of robust measurement protocols. 2) Development of new measurement tools that do not rely on DNA amplification. 3) Appropriate reference materials for calibration of the DNA concentration and validation of method performance.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** High Performance Solvents

***Submitter*:** Thomas J. Bruno

***Technological Innovation at Stake*:** Industry needs higher performance solvents to increase energy efficiency and reduce capital costs in solvent extraction processes for both new and existing products. Current applications include extraction of: 1) aromatic compounds from gasoline reformate, 2) phenols from wastewater, 3) hydrogen sulfide from liquefied natural gas, and 4) fission products from uranium and plutonium containing solutions. New classes of higher performance solvents are being considered, such as “green solvents,” for various new applications for separating olefins from paraffins.

***Economic Significance of Innovation*:** Solvent extraction processes are complex often relying on two distillation columns to recover solvent from the system. In the U.S. process industry alone, distillation columns, used with extraction, consume an energy equivalent of 120,000-180,000 barrels per day of crude oil at a cost of $2.5 billion-$3.8 billion per year, based on the current crude oil price of $60 per barrel. Higher performance solvents could significantly reduce, perhaps eliminate, the need for distillation processes by reducing the amount of solvent in the mixture, thereby allowing separation and recovery of solvent as a separate liquid phase. Reducing the cost of extraction and other separation processes could significantly expand the market for biobased products. For example, an economically viable extraction process could be key to the production of fuel-grade ethanol made from biomass. Researchers project that ethanol could replace 20-30% of fuel usage in the U.S. in a few years, with a concomitant reduction in petroleum imports and a reduction in net carbon dioxide emissions.

***Technical Barrier to the Innovation*:** New solvent extraction technologies are not being implemented because understanding of the fundamental mechanisms controlling their behavior is not available.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Thermodynamic models to predict solvent performance for various applications and the experimental methods and data necessary for model validation are not available. Models are needed to predict: 1) solvent affinity for target materials in the feed, 2) mutual solubility of feed and solvent, and 3) solvent recovery through control of temperature or other variables.

***Potential Solutions to Measurement Problem*:** Fundamental thermodynamic data are needed to enable the development of models that predict phase behavior and the ability of solvent to extract targeted materials. Development of such data could lead to modifications in existing solvents and point the way to new classes of higher performance solvents that could significantly improve performance of extraction processes for various applications.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Real Time Measurements for Pharmaceuticals and Biologics Manufacturing

***Submitter*:** Albert Lee, Mike Tarlov

***Technological Innovation at Stake*:** Pharmaceutical and biologics manufacturers currently use substantial empiricism because basic understanding of their manufacturing processes is lacking. This significantly limits their ability to model, control, and optimize manufacturing process, cut manufacturing costs, or increase throughput. FDA's Process Analytical Technologies Initiative encourages the industry to increase process understanding through adoption of process analytical technologies (PATs). Although some PATs are used now, e.g., NIR, UV-Vis, pH, dissolved oxygen, temperature, pressure, their applications are still quite limited and used more for process control and monitoring than process understanding. However, the true on-line measurement needs that would fundamentally alter the manufacturing paradigm, e.g., detection of single virions or microbe contamination, non-invasive API, active pharmaceutical ingredient, content and distribution inside each pill, concentration measurements of specific proteins within bioreactors, etc., are well beyond the capabilities of current instrumentation manufacturers because the knowledge needed to effect them is as yet unknown. Additionally, macroscale measurement technologies being used and developed today may not be applicable as the industries move toward manufacturing of personalized medicines.

***Economic Significance of Innovation*:** MIT and Price Waterhouse Coopers conducted studies of manufacturing processes and determined that the total cost of the current manufacturing infrastructure exceeded that of research and development by two or threefold. By investing in so-called "quality by design" to achieve 4.5 sigma variability in manufacturing process performance, it is estimated that drug companies may be able to reduce cost of goods sold by up to 16 percent. This would release close to $10 B in annual savings for the top 30 companies. Process understanding and process control improvement could significantly reduce batch rejection rates, currently estimated to be as high as 30% in biologics manufacturing.

***Technical Barrier to the Innovation*:** A central challenge in process instrumentation is the capability to detect chemical and/or proteins of interest at trace levels in real-time, particularly within complex media (multi-component, highly viscous, powders). Requirements range from measurement and distribution of trace amounts of the active pharmaceutical ingredient (API) in pills to detection of trace quantities of a virus or microbial contamination in bioreactors or the fill-finishing-packaging operations. Highly specific separation technologies for proteins and other large molecules are also needed.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** Real-time trace detection technology for contaminants and APIs. Quantitative performance evaluation methods require accurate and reliable standardization methodologies and technologies. This is particularly true where competing measurement technologies exist. Certified or standard reference materials can resolve such measurement method incompatibilities. These are very challenging problems in measurement science with few available commercial technologies.

***Potential Solutions to Measurement Problem*:** Innovative approaches are needed for single molecule, particle or cell detection, fluorescently tagged proteins or APIs with engineered imaging agents removable after processing and are biocompatible should be developed. Non-invasive methods are preferred driven by sterilization concerns. Improved scientific knowledge of manufacturing processes is required.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue**:** Genomics: Array-Based Comparative Genomic Hybridization

Submitter**:** Jim Hollenhorst, Agilent Technologies

Technological Innovation at Stake**:** Advances in array-based comparative genomic hybridization (aCGH) technology, the analysis of copy number changes (gains /losses) in the DNA content of tumor cells, promises to enable rapid advances in the understanding of disease and the practice of medicine. In particular, oligonucleotide microarrays, with its hundreds of thousands of probes extends the dynamic range and sensitivity of comparative genomic hybridization, promises the discovery of large scale polymorphisms in the genome with resolution orders of magnitude better than standard medical diagnostic techniques like fluorescence in-situ hybridization (FISH). The rapid development of genomic measurement tools such as aCGH will create new opportunity for medical research and diagnostics of unprecedented power.

Economic Significance of Innovation**:** The first major application of aCGH is in cancer research, and cancer diagnostics are expected to follow. Cancer is one of the leading causes of death and, beyond the significance on human quality of life, has enormous economic impact. It is truly a disease of the genome and, with this technique, scientists will be able to understand the fundamental pathology of the cell with a degree of resolution that is unheard of. This is expected to lead to rapid advances in the understanding of the disease. Cancer is also a diverse disease with many subtypes that are poorly differentiated by standard histology-based diagnostic techniques. As aCGH and other genomic techniques move into diagnostics, it should be possible to tailor treatment much more specifically, and develop pharmaceuticals that are targeted to specific cancer subtypes. Over time, this should lead to a dramatic improvement in patient outcomes. In addition, there has been tremendous interest in using aCGH in diagnosis, carrier screening and prenatal testing for developmental disorders associated with chromosome abnormalities. It is now becoming clear that a variety of other diseases, resistance to disease, and efficacy of therapeutics have the potential to be influenced by large-scale copy number variations present in every individual's genome. Thus the utility of aCGH is expected to extend well beyond cancer and developmental disorders.

Technical Barrier to the Innovation**:** DNA microarrays are in their infancy as a measurement technique. Every vendor's product measures something different and there is a paucity of measurement standards to use for reference information. This inhibits the free exchange of information between research labs and limits the speed of developing new understanding. As the technology moves into diagnostics, it will be necessary to have even better standards and methods to determine the quality of the measurements.

Stage of Innovation Where Barrier Appears: R&D

Measurement-Problem Part of Technical Barrier**:** A more rigorous set of standards and protocols are needed that provide the means to quantitatively determine the performance of arrays, i.e., assess their effective dynamic range and sensitivity, to characterize the efficacy and quality of aCGH measurements. Such will support cross-comparison between different measurement platforms.

Potential Solutions to Measurement Problem**:** A detailed understanding of the variations in array based measurements, a set of reference standards, protocols, and specifications for cross-platform comparisons.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Performance Specifications and Accurate Metering Devices for Hydrogen Engine Fuel.

***Submitter*:** David Lazier and Mike Cleary, California Department of Food and Agriculture, Division of Measurement Standards

***Technological Innovation at Stake*:** Hydrogen fuel cells based on proton exchange membrane (PEM) technologies have great potential to replace the internal combustion engine for transportation and function as stationary electricity generation sources. Fuel distribution systems are needed that both provide the necessary quantification in both retail and wholesale custody transfers and that guarantee the quality of fuel delivered. Because efficient operation and long-term viability of PEM-based fuel cells are intimately tied to membrane performance, that is irreversibly poisoned by a variety of gas phase contaminants, fuel distribution infrastructure must systematically exclude contaminants from fuel supplies and incorporate effective means of ensuring fuel supply quality along with accurate fuel quantitation.

***Economic Significance of Innovation*:** The diversity of hydrogen sources and the energy efficiency benefits of hydrogen fuel cells make the widespread use of hydrogen for transportation and stationary power an important step in protecting the future energy security of the United States. Hydrogen can be produced from many domestic sources of energy, including fossil fuels, such as natural gas and coal, and renewable resources. A fuel quality standard for this fuel is necessary to insure proper performance of the vehicle designed to use hydrogen fuel.

***Technical Barrier to the Innovation*:** Contaminants such as ammonia, carbon monoxide, carbon dioxide, formaldehyde, formic acid, hydrocarbons, and sulfur compounds harm catalyst coated proton exchange membranes of a fuel cell reducing its efficiency, performance and reliability. Determination that these contaminants are not present in hydrogenous fuels are needed to ensure that the marketplace can be monitored for compliance ensuring that the hydrogen fuel is produced and sold that meets these fuel quality standards.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** A fuel quality standard for hydrogen fuel does not exist. Additionally, standardized sampling and testing procedures do not exist for hydrogen fuel and must be developed. Advances in flow metering technologies and standards are also needed.

***Potential Solutions to Measurement Problem*:** R&D to develop fuel quality standards, sampling and testing methods must move forward in order to have them in place by the time hydrogen fueled vehicles become commercially available to the motoring public.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Electric Power Grid Dynamic Measurements

***Submitter*:** G. Stenbakken

***Technological Innovation at Stake*:** This innovative measurement of power grid dynamics, which combines signal waveform measurements accurately related to UTC signals from GPS satellites, would allow estimation of the state of the grid and potentially could be used to predict its instability and to control the grid for improved reliability.

***Economic Significance of Innovation*:** Improved electric power grid reliability would help efficiently balance power supply with demand, and will help avoid the significant economic costs of blackouts. A blackout in 2003 cost NY alone $1.1B – about $36M/hour.

***Technical Barrier to the Innovation*:** Currently multiple phase measurement units (PMUs) from different manufacturers give different results for the same static conditions. Thus, these units are not completely interchangeable today. The future industry need is for standard methods for measuring their dynamic performance, which will be important when PMUs are used to control the power grid.

***Stage of Innovation Where Barrier Appears*:** Production. This equipment is being manufactured and used today with adequate static signal performance. However, standard test methods, calibration procedures, and facilities do not exist for dynamic signal characterization. Thus, the barrier is at the production stage for dynamic signal PMUs.

***Measurement-Problem Part of Technical Barrier*:** Relating absolute time to a dynamic signal with the required accuracy and with the ability to document the resultant uncertainty.

***Potential Solutions to Measurement Problem*:** Have a neutral facility develop and perform calibration procedures for phase measurement units that all manufacturers and users (utilities) can agree upon.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Superconductor technology for energy reliability.

***Submitter*:** Jack Ekin, Loren Goodrich, Najib Cheggour, and Daniel van der Laan

***Technological Innovation at Stake*:** The electric power utilities need to upgrade the electric power grid in the following areas: (1) phase compensation to mitigate black out, (2) energy transmission to urban centers, (3) electric power conditioners for sensitive industries, and (4) electric fault current limiters. Devices made possible by the novel (YBCO) superconductors represent a major new technology that has the potential to address each of these areas.

***Economic Significance of Innovation*:** (1) The disruption and cost of the black out of the Northeast in August 2003 could have been prevented with fast response superconductor synchronous condensers. The economic cost of the blackout is estimated between \$6B-\$10B. The Tennessee Valley Authority is currently testing prototypes of these devices in their power grid. (2) Urban underground superconducting transmission lines can provide increased power to urban centers without increased real estate purchases and excavation. (3) Loss of power to computing centers and continuous-production-line industries (e.g., plastics, semiconductor manufacturers) results in complete facility shut down and restart with considerable time and money loss. (4) Superconducting fault current limiters would result in about a 10 times reduction in fault current levels compared to conventional breakers. Thus, future grid components would not need to be over designed, which would reduce cost across the entire power grid. Fault limiters with these unique properties cannot be made from conventional materials such as copper wire. The U.S. Department of Energy estimates that the market for superconductor fault current limiters in the U.S. alone will be several billion dollars over the next 15 years.

***Technical Barrier to the Innovation*:** Existing superconducting power grid prototypes are expensive and have limited current density capability. They are also not mechanically robust. In contrast, new classes of superconductors (e.g., Yttrium Barium Copper Oxide, YBCO) have good mechanical integrity and offer 5 to 10 times as much performance and potential cost reduction. However, these second generation wires need to be manufactured in long lengths. The main barriers are maintaining properties and reducing cost during the scale-up phase, during which performance data and feedback to industry are required.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** High currents, low temperatures, and high electro-mechanical forces combine to form challenging technical barriers for characterizing these materials. The measurements are complex and require the quick development of innovative measurement techniques to provide immediate and ongoing performance feedback to industry.

***Potential Solutions to Measurement Problem*:** Development and commercialization of new superconductor measurement instruments including variable-temperature critical-current measurements, bi-axial tape bending instrumentation, low temperature delamination test techniques, and variable-angle, high-magnetic-field strain testing methods. Other important material property measurements such as composition, grain alignment, and microstructure will also be needed for a successful scale-up. An extensive database of all performance properties is needed for advanced designs of second generation YBCO superconductors.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** High-speed electrical systems for broadband communications

***Submitter*:** Dylan Williams, Paul Hale

***Technological Innovation at Stake*:** Telemedicine, video on demand, internet gaming, information storage, computing systems, and Voice over IP are only a few examples of business sectors that require increasingly greater information-carrying capacity from the telecommunications, IT, and wireless communications sectors. The most cost-effective way to meet the demand for greater information-carrying capacity is to increase the speed of the communication links. This central goal of the telecommunications industry has driven the speeds, and complexity of the electrical waveforms employed in these systems, beyond the current capacity to measure them.

***Economic Significance of Innovation*:** National telecommunications spending will reach $850B this year, and worldwide spending will top $2.4 trillion. Capital expenditures on telecommunications in the US totaled $17B this year. Sales in this market are based on the ability to deliver high-speed, reliable, and interoperable communication systems with greater information-carrying capacity and at a lower cost than our foreign competitors. Higher speeds are key to obtaining greater information carrying capacity.

***Technical Barrier to the Innovation*:** Broadband communications systems are so large, complex, and expensive that system providers must rely on multiple manufacturers to produce interchangeable components and subsystems. Yet different test equipment gives different outcomes, resulting in false pass/fail results and raising the costs. Standards developed for the telecommunications industry must now guarantee the performance and interoperability of receivers, transmitters, and switching systems for the current 10 Gb/s workhorses now in wide use, as well as for the newer 40 Gb/s systems currently being fielded. Eventually these standards will also have to support the even faster 80 Gb/s and 160 Gb/s optical links and switching networks being developed in the labs.

Standards for 10 GB/s links require complex electrical waveform measurements to 30-50 GHz, and the faster 40 Gb/s links require complex electrical waveform measurements to well over 100 GHz, the maximum frequency of even the highest-speed electrical waveform instrumentation. The difficulty of performing the electrical waveform measurements increases with frequency, and the metrology required to support waveform measurements at these frequencies is in its infancy.

***Stage of Innovation Where Barrier Appears*:** R&D and Production

***Measurement-Problem Part of Technical Barrier*:** Accurate electrical waveform standards for calibrating electrical waveform measurement instrumentation from 2.5 GHz to 110 GHz and above as needed. The industry desperately needs traceable measurements of electrical eye-patterns and other complex electrical quantities over the entire spectrum to 110 GHz. These needs are shared by the telecommunications, IT, wireless, and semiconductor industries.

***Potential Solutions to Measurement Problem*:** Develop appropriate electrical waveform standards and calibration algorithms.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Inexpensive, compact, and reliable blue and ultraviolet laser sources

***Submitter*:** John Lehman

***Technological Innovation at Stake*:** Inexpensive, robust laser-based (fluorescence) measurement systems related to detection of hazardous biological and chemical aerosols. Other impacted innovations include development of high definition DVD players/recorders and compact, robust, low cost water purification systems.

***Economic Significance of Innovation*:** Currently, blue laser diode manufacturing alone is a multi-billion dollar industry. Blue and UV lasers are applicable to optical communications, medical procedures, and consumer products such as DVDs.

***Technical Barrier to the Innovation*:** Long term stability, reliability, lifetime testing as well as aging, hardening and damage of laser optics limits product development and reliability.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** There is no laser power measurement capability for low power, continuous-wave blue and UV laser sources, traceable to a national measurement institute in the world. National and occupational laser safety standards require equipment for evaluation of laser power to be traceable to NIST standards.

***Potential Solutions to Measurement Problem*:** Develop transfer standards for the wavelength range 260 nm to 400 nm that have linear response up to 20 mw power levels. Adapt and evaluate primary laser power standards for the laser wavelength range 260 nm to 400 nm. Establish efficiency, lifetime and reliability testing of sources. Establish measurement detectors resistant to age hardening and damage with advanced materials (e.g. carbon nanotube coatings).

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Carbon Nanotube Identification

***Submitter*:** John Lehman

***Technological Innovation at Stake*:** Because of their strength, flexibility, and unique properties, carbon nanotubes (CNTs) are promising materials for application to a wide range of potential or improved products. As with any material, proper characterization and fitness-for-use testing are required for product scale-up. Simple, non-destructive and cost-effective tests for carbon nanotube identification and characterization are needed for manufacturing process optimization, safety regulation, process control and material enrichment.

***Economic Significance of Innovation*:** CNTs are a critical part of the nanotechnology infrastructure. Due to their special properties, they have applications in areas such as energy storage, molecular electronics, sensors, and materials. However, CNTs are expensive, costing $60-750/g depending on purity, and future prices need to be far less in order for them to appear in commercial products and to help nanotechnology realize its potential. Richard Smalley, Nobel prize recipient, identified cost reduction as the “single biggest limiting factor to quickly moving nanotubes into the marketplace.” High costs are driven by low product yield, forcing producers to endure complicated, expensive purification processes. By providing new measurement tools, true process optimization can begin.

***Technical Barrier to the Innovation*:** Current manufacturing processes do not simply produce a single type of CNT. Instead, they inherently produce a mixture of CNT species, along with unwanted chemical impurities (3 - 50 %). Advanced, cost effective analytical techniques are needed so that CNT manufacturers, product developers, and regulatory agencies can truly “see” what they have.

***Stage of Innovation Where Barrier Appears*:** R&D, Production

***Measurement-Problem Part of Technical Barrier*:** Rigorous process control is not feasible today, because producers do not know what type of CNTs are in a given batch. Additionally, products differ between manufacturers, and CNTs from a single supplier can vary. Better control, which requires better measurement techniques, will yield better consistency. Quantitative data on chirality and diameter as well as semiconducting-to-metallic ratio determine the performance of field-emission devices, fuel cells, optical detectors and multifunctional composite materials.

***Potential Solutions to Measurement Problem*:** New processes and screening techniques are needed to identify and characterize CNTs. One possible approach being explored at NIST is a two-tiered screening process, which matches characterization precision and accuracy with application needs. Tier 1 methods rapidly screen bulk CNTs for batch certification and high-volume products, such as polymer composites. Tier 2 methods quantify CNT species, including chirality, diameter, and defects - key attributes that dictate properties.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Single Photon Photonics

***Submitter*:** Sae Woo Nam, Robert Hickernell

***Technological Innovation at Stake*:** Quantum communications takes advantage of quantum mechanical properties to transfer information in a provably secure manner. Additionally, quantum computing systems process information potentially much more quickly than even the best classical computers. These quantum information systems, when photonics-based, require sources of countable photon states (or "single photon sources") and photon-number-resolving detectors, which are under development. Single photon photonics is also being developed for measurement of low light levels for ranging, fluorescence in chemical and biological samples, and other applications. Simply put, the innovation at stake is the creation, delivery, and detection of small numbers of photons.

***Economic Significance of Innovation*:** Innovations in single photon photonics will result in significantly reduced product development times, ultra-secure communication in the military, intelligence, and financial sectors, and increased public health and safety (increased early medical diagnosis probability, increased hazardous agent detection). The potential economic impact of quantum information processing is huge. The cyber-security industry alone had $3.8B revenue in 2005.

***Technical Barrier to the Innovation*:** To reach the required error level per pulse (<1% for quantum computing), GHz rates, and longer transmission lengths, single photon sources need higher emission efficiencies, optimum operating wavelengths, and narrower linewidths. For single photon detectors to reach efficiencies of greater than 95% at visible and near-IR wavelengths, they require improved materials and optical design. Low dark count rate is essential. Transmission media are needed with little or no loss.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** High-performance sources of single and few photons and detectors are mutually dependent for verification of their specifications. The metrology at single photon levels of light is not standardized. It is difficult to relate conventional measurements of light power (e.g., Watt) to a single or few photons. The dynamic range of such a measurement would be nineteen orders of magnitude. At NIST, our best measured quantity is time; we do this to 1 part 10^{15}. Confirmation of the suitability of components for quantum information applications requires appropriate test-beds.

***Potential Solutions to Measurement Problem*:** R&D in materials, optical cavity design, and fabrication processes would decrease the error rate and increase the emission rate of single photon sources and improve the quantum efficiency and response times of detectors. Solutions in measurement R&D would decrease noise sources and accurately measure efficiencies of single photon sources, detectors, and transmission media.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Wide-Bandgap Semiconductor Photonics

***Submitter*:** Norman A. Sanford, Robert K. Hickernell

Technological Innovation at Stake: Wide bandgap (WBG) compound semiconductor technology for: (i) Development of solid-state, general-purpose lighting, based on light-emitting diodes (LEDs), for substantial energy cost savings and reduced environmental impact. (ii) Ultraviolet/visible lasers and LEDs for homeland security applications including chemical / biological detection, and healthcare needs such as cancer detection. (iii) WBG nanostructures for use in secure communications.

***Economic Significance of Innovation*:** Recently, the DoE has predicted that solid-state lighting (SSL) could partially displace the use of incandescent and fluorescent lamps, thereby reducing lighting energy consumption by 33% and resulting in consumer savings of $128 B from 2005 to 2025. SSL has the potential for disruptive technological growth and the creation of new, high-quality U.S. jobs. The impact of other emerging aspects of WBG technology is more difficult to quantify but still of great importance.

***Technical Barrier to the Innovation*:** A major barrier is the lack of an economically viable native growth substrate. The prevailing use of non-lattice-matched substrates results in defect-ridden material. There is also a poor fundamental understanding of III-N alloys, their doping, and optimum processes and tools for producing high quality material. Typical commercial LEDs display unacceptably low radiative efficiency.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Measurement challenges include: in-situ growth diagnostics of material composition, growth rate, etc.; carrier transport and recombination mechanisms resolved on the nanometer scale; measurement of electronic bandstructure, hetero-structure band offsets, and recombination coefficients; evaluation of the roles of defects and microstructure in optical and transport properties; nanoscale measurements of alloy composition and phase separation; methodology for the accurate measurement of quantum efficiency; and direct measurement of minority carrier diffusion length. The vast majority of data on the III-nitrides has been derived from inherently inferior material. Thus, manufacturers are “shooting in the dark” in many aspects of device design and process optimization. A metrology breakthrough could have enormous leverage in technological development.

***Potential Solutions to Measurement Problem*:** Measurements must be made to establish fundamental electrical, optical, and mechanical properties for III-N alloys grown by various methods using the highest quality native substrates. Nanoscale measurement tools must be developed. The new high-quality data will then provide manufacturers a basis to evaluate their material and guidance to steer their processes.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Room-Temperature Magneto-Cardiography

***Submitter*:** Dave P. Pappas

***Technological Innovation at Stake*:** Non-invasive measurement of the magnetic signal from ionic currents can be used to build up an image and electrical model of the heart. The magnetic fields from these currents are on the order of 1 x 10-12 tesla (a field about 100 million times smaller than the earth's field). This technique is often referred to as magneto-cardiography (MCG), and represents the state of the art in non-invasive diagnosis of cardiac problems. The innovation here is the room temperature function.

***Economic Significance of Innovation*:** Systematic screening of and correct diagnosis of arrhythmias in heart activity could save thousands of lives every year and billions of dollars in medical costs of unnecessary heart surgery. MCG would allow radiologists to more accurately diagnose severe heart ailments and distinguish between problems that could be helped with surgery and those that couldn't. Existing technology for measuring the low level magnetic fields encountered in MCG uses liquid helium cooled devices. This method is very expensive and not practical for routine screening. Development of devices that operate at room temperature would bring MCG into the mainstream of medical practice.

***Technical Barrier to the Innovation*:** The limitations arise from the fact that the low temperature devices must be kept in a cryostat next to the patient. This limits the number of sensors, the distance from the heart to the sensor, and the geometry of the sensor array. If a technology could be developed that relied on integrated circuit devices that run at room temperature then there could be a self-contained unit comprised of multiple sensors that can be kept close to the patient.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The measurement of ultra-low fields using room temperature devices requires the use of resistors that are made from magnetic material. The physical properties of the films, from the macroscopic shape to nano-scale defects and atomic composition all play a role in the sensitivity and noise of the devices and require new measurement techniques.

***Potential Solutions to Measurement Problem*:** R&D to develop very soft (i.e. easily switched) magnetic films that deliver a large signal with low noise when a magnetic field is applied to them. These devices are referred to as magneto-resistors (MR). MR's are at the core of every high density computer hard disk drive. However, this technology has not yet made the jump from the data storage area to the general-purpose magnetic field area. With recent development of MRs that change by 400% in a magnetic field it is imminent that these devices will take over the market in low field metrology.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Coherence in Single Crystal Materials for Solid State Quantum Computing

***Submitter*:** David P. Pappas, Raymond W. Simmonds

***Technological Innovation at Stake*:** Preservation of quantum information in solid state systems will enable a new paradigm in computing, called Quantum Computing. A successful, scalable implementation of QC will enable us to do some important types of calculations that are considered to be intractable on classical computers. These operations include, but are most likely not limited to, simulating large molecule folding sequences for DNA and large scale biological systems, search algorithms for databases, data encryption and decryption.

***Economic Significance of Innovation*:** The economic impacts of quantum computing would be spread over many areas. Initially, it can be expected that large scale quantum computers would be operated as a centralized facility that would accept queued jobs on a priority basis. These facilities would be available to users from a wide range of applications. The power of this technology will allow us to perform extremely complex simulations, opening up innovative possibilities for the fields of engineering, biology, chemistry, and physics.

***Technical Barrier to the Innovation*:** The main problem in quantum computing is decoherence. This is the process whereby the prepared state is scrambled into some other, undesired, state before it can be used in a computation. Many systems are currently being investigated for use in quantum computers, including superconducting circuits. These circuits are attractive because they can be fabricated with standard processing techniques. This means that they can be scaled up to circuits that include thousands of elements. At present, the main sources of decoherence in these devices are in the materials. For example, amorphous materials such as silicon and aluminum oxide (glass and ceramic) have atoms that are not tightly bonded in one place. This allows for extra, uncontrolled quantum states to exist in the device. For these materials, it is necessary to crystallize them to achieve coherence times sufficient for meaningful computations.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The measurement of quantum decoherence in materials requires several key competencies. These include the ability to grow single crystal multilayers, fabricate and image nano-scale structures, and measure the coherence times in quantum devices. Growth of these crystalline materials must be accomplished in ultra-high vacuum using state of the art molecular beam epitaxy. This must be followed up be fabrication in a state-of-the-art lithography facility, and testing using well designed quantum devices. Careful and consistent measurements must be made in order to understand and track the physical mechanisms for coherence loss in these devices.

***Potential Solutions to Measurement Problem*:** A concerted effort needs to be directed towards developing novel, nanostructured materials and devices that preserve coherent states in solid state systems. A systematic approach to tunnel barriers and dielectrics is needed to enable this technology.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Cooling of Electronics

***Submitter*:** Cameron T. Murray, 3M Center, Building 209-1C-30, St. Paul MN 55144

***Technological Innovation at Stake*:** Thermal Interface Materials (TIMs) are used to connect heat generating integrated circuits to some form of a heat sink. This cooling of the electronic component is critical for high reliability and lifetime of the component. As the heat flux and total heat load increase there is demand for improved TIM materials showing lower thermal resistance.

***Economic Significance of Innovation*:** Electronic products dominate the economies of most of the developed world. TIM materials are used in nearly all electronics assembly to provide a path for heat removal. High performance TIMs are needed for high heat flux applications such as servers, supercomputers, hybrid vehicles, and military/aerospace electronics. Even high end desktop and laptop computers are projected to reach performance levels requiring improved TIMs. The cost of not being able to cool a particular application is a loss of the business for that company. So each company has their application at risk if it cannot be cooled.

***Technical Barrier to the Innovation*:** Because of barriers to accurately measure thermal resistance and bulk conductivity of TIM materials, designers of electronic assemblies are not able to correlate their in-use performance to these metrics. These uncertainties prevent designers from making material selection without considerable prototype testing.

***Stage of Innovation Where Barrier Appears*:** Marketplace

***Measurement-Problem Part of Technical Barrier*:** The standard measurement method for thermal resistance and TIMs is ASTM D5470, a new revision of which is due in 2006. Traditionally these apparatus have been custom built for each vendor and consumer, there has not been one standard design nor instrument manufacturer to establish a standard of design. With such a wide variety of designs round robin testing through ASTM has found poor intra and inter laboratory correlation. There does not exist a good design guide for this test method and there is no group that can evaluate a design and identify sources of error. In addition there does not exist a good set of calibration standards that mimic the type of material tested with this method.

***Potential Solutions to Measurement Problem*:** Creation of a design guide for a guarded hot plate (ASTM D5470) test method and establishment of a set of calibration standards with the same form and approximate thermal performance expected of the TIM materials. The calibration standards would have to be available for purchase with NIST certification. Also, a service should be provided to evaluate existing equipment to determine if it meets a suitable standard of accuracy.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** System Energy Efficiency Performance Measurement

***Submitter*:** Mark D. Newton, Dell

***Technological Innovation at Stake*:** Lack of a system-level energy efficiency measurement system to guide the design of electronic products is resulting in prescriptive component and use-state threshold requirements that are preventing manufacturers from cost-effectively optimizing product performance and overall energy efficiency. These limits are hindering industry's ability to fully optimize integrated hardware and software solutions and to cost effectively deliver required features to the consumer.

***Economic Significance of Innovation*:** Personal computers and monitors currently account for approximately 40% of all energy consumed by office and telecommunications equipment in U.S. commercial buildings. LBNL estimates that office equipment energy efficiency improvements have the potential to save up to 17 TWh/year1. This is a potential savings of about 0.5% of total electricity consumption in the U.S. (about ~280,000 households), with a corresponding reduction in emissions generated from electricity production. Efficiency optimized household IT equipment and other electronic devices would add to this estimated savings.

***Technical Barrier to the Innovation*:** Lack of robust algorithms related to interdependencies of component-level power consumption contributors and variability of consumer use behavior are the major technical obstacles.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Complexities of system-level measurement that must be taken into account include differences in product type, performance level, network and infrastructure considerations, IT management protocol, use states, and consumer use behavior. These measurements can be used in the development of the needed algorithms (above).

***Potential Solutions to Measurement Problem*:** Empirical and theoretical approaches to this problem have been considered. Some approaches may involve the use of algorithms to analyze the impact of specific input parameters, other methods may incorporate dynamic data. A number of power-performance metrics have been proposed and some of them have been used to compare different products on the market. The "MIPS per Watt" metric, or reverse of "energy-per-operation" has been used for comparing low-end microprocessors. Software is commercially available to calculate performance-energy characteristics with set constraints.

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1 http://www.lbl.gov/Science-Articles/Archive/net-energy-studies.html

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Millimeter-wave and Terahertz Systems

***Submitter*:** Thomas P. Crowley

***Technological Innovation at Stake*:** New devices, sensors and systems for use at frequencies between 100 GHz and 10 THz are being developed. Future development of these products is threatened due to the lack of standards in this region of the electromagnetic spectrum which lies between traditional microwaves and infrared.

***Economic Significance of Innovation*:** The present market for products between 100 GHz and 10 THz is small, but is expected to grow significantly. A rough idea of the potential market can be obtained by looking at frequencies from 30 to 100 GHz. This frequency range includes applications for radars, communications and optoelectronics and includes companies such as Raytheon, Agilent, and L3 Communications, as well as a number of smaller companies. Many of these applications (such as optoelectronics) are expected to expand to frequencies above 100 GHz in order to operate at higher speed. In addition, new markets involving medical imaging, proteomics, spectroscopy, and homeland security are expected to develop using frequencies near 1 THz.

***Technical Barrier to the Innovation*:** There are no accepted standards for power measurements in this region of the spectrum and therefore power sensor manufacturers encounter difficulties in selling their products since they cannot claim traceability. In addition, people who use those sensors to develop new signal sources and systems cannot be certain that their devices will operate properly in conjunction with those of other manufacturers.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Accurate microwave and infrared power measurements are based on comparisons with DC power. Since the power sensors inevitably have a slightly different response to the microwave or infrared radiation than they do to a DC signal, it is crucial to characterize this efficiency accurately. A similar approach is expected for the millimeter wave and terahertz region that lies between microwaves and infrared. The efficiency characterization of a primary standard requires a special set of tests that typically have only been performed at national laboratories. However, once a primary standard is established, it is relatively easy to characterize the efficiency of other sensors.

***Potential Solutions to Measurement Problem*:** One solution will be the development of primary power standards at a national laboratory such as NIST. This will require the development of an independent power measurement capability similar to those presently available at lower frequencies. Full characterization of the detection efficiency will be pursued. Manufacturers could then base their efficiency claims on NIST's primary standard. A second solution would be a comparison of the commercial power sensors with each other. If the existing sensors are in agreement, this will provide confidence that various components will work well together. A disagreement, however, is liable to force the need for a national standard.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** RFID Device Interoperability, Security, and Adoption

***Submitter*:** Jeff Guerrieri**,** Mike Francis, David Novotny, Perry Wilson

***Technological Innovation at Stake*:** The broad adoption of emerging radio-frequency identification (RFID) systems, especially those mandated by the government for identification applications, is being delayed due to lack of metrology support. Load modulation (signal return from the RFID chip) and reader magnetic field and other parameters are critical to verifying performance. Interoperability of readers and chips is essential. Preventing eavesdropping and skimming are important to protecting privacy of personnel.

***Economic Significance of Innovation*:** RFID technology is becoming widespread, and anticipated applications include inventory control and secure access to buildings. RFID inventory control and tracking is rapidly growing with use by industries ranging from high volume retailers to specialized secure shipping. Secure access using RFID is becoming the norm in both industry and government The US Government alone anticipates issuing 14 million RFID "ePassports" per year, with an economic impact of about $1.4 billion per year.

Furthermore, in the near future two million government workers and a similar number of government contractors will have government-issued RFID badges. Calibration of load modulation, reader magnetic field, and other parameters are needed by government and industry to ensure the best possible system performance and system interoperability.

***Technical Barrier to the Innovation*:** Vendor testing is generally proprietary and an unbiased source of performance verification is needed. Testing to ensure that RFID data are not acquired by unauthorized individuals requires expensive equipment and optimization of transmit and receive circuits.

***Stage of Innovation Where Barrier Appears*:** Marketplace (Performance verification and security testing)

***Measurement-Problem Part of Technical Barrier*:** Standardized test parameters need to be established to test readers for interoperability (potential barrier) and security, such as shielding against eavesdropping and the susceptibility of RFID tags to remote activation.

***Potential Solutions to Measurement Problem*:** NIST has played a leading role in developing tests for verifying electromagnetic performance of prototype ePassports and readers and for determining vulnerability to eavesdropping and skimming. NIST has begun to extend its knowledge of measuring the electromagnetic fields generated by antennas, to calibrating and measuring the electromagnetic fields generated by RFID readers and returned by RFID chips. These tests can be extended to verify performance for other RFID applications and ensure protection of sensitive data.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Emerging Sub-Millimeter Wave Systems

***Submitter*:** Mike Francis, Katherine MacReynolds, Ron Wittmann, Perry Wilson

***Technological Innovation at Stake*:** The development and adoption of satellite, communications, radar, aerospace, radiometer, and defense systems in the frequency range 110 GHz to 500 GHz is currently being inhibited by the lack of solid antenna parameter metrology support. Antenna parameters (gain, pattern, polarization) are critical to verifying performance, optimizing, diagnosing, and maintaining these critical systems.

***Economic Significance of Innovation*:** Well characterized antennas in both existing and emerging satellite, communications, radar, aerospace, radiometer, and defense systems play a significant role in the value of these systems. A specific example is the radiometer antennas used for weather, remote sensing, and public safety systems. It is estimated that reducing overall uncertainty from approximately 2.8 dB to at least 2.2 dB would improve weather forecasting and tracking and result in an implied benefit gain of $700 million per year to the US economy Long term goals of further improving radiometer uncertainty to the 1 dB level would result in an estimated benefit closer to $1 billion in 2003 dollars.

***Technical Barrier to the Innovation*:** The electronics and hardware needed to make 110 GHz to 500 GHz antenna parameter measurements is very much in the prototype stage. Antenna ranges and near-field scanners need to be developed and researched to define and overcome metrology challenges and to define and improve uncertainties. Measurement methods, which have served well at lower frequencies, may need extensive modification, or they may need replacement with quasi-optical techniques.

***Stage of Innovation Where Barrier Appears*:** End Use (System design and performance verification)

***Measurement-Problem Part of Technical Barrier*:** Industry cannot develop both the new theory and metrology needed as they are focused on system design. Providing traceability to a US National Laboratory remains a unique and essential NIST function. The cost of electronics and hardware in the 110 GHz to 500 GHz frequency range is prohibitive for most companies and universities.

***Potential Solutions to Measurement Problem*:** NIST has played a leading role in developing and disseminating near-field antenna metrology theory and practice. NIST has developed a world first dynamic laser tracker system that allows the implementation of probe-position error correction on the current NIST millimeter wave planar scanner. This capability potentially enables accurate near-field scanning measurements to 500 GHz. Missing is the RF system needed for the actual data acquisition. NIST can provide a solution by acquiring electronics and hardware, beginning a measurement program in the 110 GHz to 500 GHz range, identifying challenges and uncertainties, researching solutions and improvements, and disseminating this capability to US industry and agencies.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** High End Computing

***Submitter*:** Ronald F. Boisvert

***Technological Innovation at Stake*:** Design and optimization of complex products and processes can be greatly accelerated through the use of modeling and simulation. High end computers (HEC), i.e., computer systems comprised of hundreds to thousands of processors interconnected with high-speed data paths, are critical enablers of this technological innovation.

***Economic Significance of Innovation*:** High end computing is already heavily employed in large scale manufacturing industries, such as oil and aerospace. By allowing much more facile exploration of design space than is possible in building physical models, such techniques typically yield better designs much faster and cheaper than before. More widespread use of such technologies could yield highly needed competitive edge in many other industrial sectors. According to a 2004 report of the Council on Competitiveness which surveyed industrial computer users, "dramatically more powerful and easier to use computers would deliver strategic competitive benefits."

***Technical Barrier to the Innovation*:** Matching potential modeling and simulation applications to an appropriate HEC architecture, which is necessary to attain performance commensurate with investment, is very difficult. HEC systems are highly varied and complex, with performance depending not only on individual processor speed, but also on the details of memory hierarchies, processor interconnects, and the system software used to translate user programs into machine instructions. In addition, the performance of an HEC system depends strongly on the application. The risk of investing in costly infrastructure when the return cannot be accurately predicted is a substantial barrier for companies considering use of HEC.

***Stage of Innovation Where Barrier Appears*:** End Use

***Measurement-Problem Part of Technical Barrier*:** The difficulty of predicting the performance of a given application on a complex existing or proposed HEC system is a challenging measurement-related problem. Performance measurement and prediction for high-end computers remains difficult as researchers and vendors develop new variants for HEC architectures on a continual basis. Benchmarks have traditionally been the best way for a purchaser to gauge the performance of such systems. However, most companies cannot afford to develop extensive benchmarks tailored to their work. Simple measures such as theoretical peak performance or the ubiquitous LINPACK benchmark do not provide an accurate prediction of sustained throughput for real applications. OSTP's May 2004 Federal Plan for High End Computing cites a need for improved performance measures, including synthetic benchmarks that target computational kernels typical of high-end applications, as a critical need.

***Potential Solutions to Measurement Problem*:** Development of new benchmarks, methods, protocols, and tools, for the measurement of performance of HEC systems can provide potential users with more realistic estimates of the utility of a particular computing architecture. Benchmarking efforts have been tried before, by research groups and consortia, but failed through inflexibility and lack of consensus.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Quantum Cryptography

***Submitter*:** Alan Mink

***Technological Innovation at Stake*:** Quantum cryptography for secure and efficient Internet communications for the future. Quantum cryptography is a multidisciplinary research area overlapping physics, electrical engineering and computer science. Quantum properties of physical systems have the potential to provide the basis for secure and efficient Internet communications.

***Economic Significance of Innovation*:** Current cryptography is vulnerable to decryption from advances in computing through the development of breakthrough factoring algorithms. Alternative secure cryptography technologies must be developed if we are to continue to rely on electronic communications for exchange of critical information over networks, which underpins the entire U.S. economy. By exploiting certain phenomena of quantum physics, quantum cryptography can provide breakthrough levels of security than currently exists.

***Technical Barrier to the Innovation*:** The exploitation of quantum systems themselves is necessary but insufficient to develop such secure cryptography technologies. Related work in algorithms, protocols and performance measurements are equally important to safe guard and develop such secure cryptography. Furthermore substantial engineering effort is needed to develop a cost effective and practical system that could coexist with the existing telecommunications infrastructure. The barriers to achieving long distance quantum cryptography over standard Internet links are quantum memories/repeaters, quantum protocols and performance evaluation methods. Although short distance, dedicated point-to-point partial systems have been demonstrated, no research group worldwide has been able to demonstrate anything close to the desired long distance, integrated complete system.

***Stage of Innovation Where Barrier Appears*:** R&D and Production

***Measurement-Problem Part of Technical Barrier*:** There are no commonly accepted standards for measuring and verifying the performance of quantum cryptographic systems. The absolute secure aspect of a cryptographic system depends on its correct implementation. Measures, criteria and tools that obtain these measures and evaluate them are needed to determine if a system qualifies as secure within acceptable limits.

***Potential Solutions to Measurement Problem*:** The NIST quantum cryptographic testbed provides a metrology infrastructure for research, testing, calibration and technological development. NIST could use the testbed to develop tests and measurements for quantum cryptographic system evaluation. One example is evaluating the randomness and predictability of the received quantum data stream within the photonic subsystem of the NIST quantum key distribution system, a critical building block of any quantum cryptography facility.

Case Study – Measurement Needs

***Technology at Issue*:** Quantum Computing

***Submitter*:** Ronald F. Boisvert

***Technological Innovation at Stake*:** Recent advances at the intersection of quantum physics and computer science have opened up the possibility of using the quantum properties of physical systems as the basis for computation. The exploitation of quantum systems themselves for computation is a breakthrough which could sustain future progress in computer technology.

***Economic Significance of Innovation*:** The semiconductor industry is now the largest US manufacturing industry, riding the wave of global sales reaching $213B in 2004. Progress in miniaturization in semi-conductors, which has been the technological engine driving steady increases in computer power for some 40 years, may stagnate in the foreseeable future as domain sizes reach atomic levels and quantum effects begin to dominate. Fundamental new computing technologies must be developed if we are to continue to increase computing power and capacity. Also, since quantum computers theoretically can perform certain tasks (e.g., factoring, searching, and simulation) much faster than classical systems, there is great potential for applications impossible with current technology.

***Technical Barrier to the Innovation*:** The manipulation and control of quantum systems is extremely difficult, and only a few research groups worldwide have been able to demonstrate rudimentary capabilities.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Many physical systems of widely varying capabilities are currently under study as potential bases for quantum computers. Limited funding means that attention must be focused on best prospects. Comparatively little effort has gone in to evaluate and compare such technologies objectively, using measures of their information processing reliability, capacity, and efficiency.

***Potential Solutions to Measurement Problem*:** The so-called DiVincenzo Criteria for determining if a physical system is usable for quantum computing have been very helpful in making gross evaluations of proposed technologies. Further progress requires a more detailed and carefully presented set of benchmarks which can be used to evaluate the information processing capabilities of a physical system.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Video Analysis and Content Extraction (VACE)

***Submitter*:** Marty Herman, Leslie Collica

Technological Innovation at Stake: Accurate video content extraction and perception of video images for intelligence analysis, military, and commercial applications. Video content includes recognizing people, objects, events, and scene analysis to derive understanding of what is occurring in the scene. This represents a new class of video analysis systems. For example, a system analyzing a video clip may determine not only that there are people and cars and a building in a scene, but also understands that the people are running from a bank to a car, which may signify a possible event (bank robbery in progress) to investigate.

***Economic Significance of Innovation*:** This is a high technical risk research area which has potential for high payoff in improving the quality of intelligence information derived from video images for Homeland Security and national security applications. This is also high payoff in broader commercial applications for next generation video search, summarization, filtering, and mining products which can recognize people and objects from video (rather than just retrieving images and video clips based on simple indexing).

***Technical Barrier to the Innovation*:** This is a challenging, new technology area still in the research/pre-competitive stage. There is general agreement that emerging systems do not perform very well and that much research and development is needed to improve these systems to the level of accuracy and reliability needed by the intelligence community, and by commercial search systems.

Stage of Innovation Where Barrier Appears: R&D and Production

***Measurement-Problem Part of Technical Barrier*:** Appropriate metrics and evaluation methods need to be developed to benchmark accuracy and quality evaluation of systems, to help push the state-of-the-art to the level of reliability needed by intelligence analysts, and eventually for commercial products. Research in measuring performance has begun, but needs greater focus to accelerate this technology.

***Potential Solutions to Measurement Problem*:** Perform further research and evaluations, in collaboration with the intelligence community, to better understand the metrics needed in intelligence analysis applications, and in collaboration with the research community to perform evaluations to push the state-of-the-art towards reliable, commercialized systems. Need to understand tradeoffs between custom systems/test-sets and general purpose systems/test-sets. Evaluations are needed to understand the appropriate test data, methods, and metrics, for applications to measure accuracy of a new class of video retrieval and motion image systems.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Millimeter-Wave Wireless Personal Area Networks

***Submitter*:** Kamran Sayrafian, NIST

***Technological Innovation at Stake*:** The wireless broadband communication industry anticipates the innovative use of millimeter wave technology for high speed short range applications. CMOS chips for mmWave, which allow low-cost, low-power applications, are currently under research/development. The IEEE recognizes the potential of this new application for mmWave and has set up a task group to create a standard for the physical layer at these frequencies.

***Economic Significance of Innovation*:** Demand and production of the mmWave-based wireless systems is accelerating due to the relatively clean and unlicensed band (57-64 GHz) allocated by the FCC, increasing demand for higher data rate and decreasing costs of the corresponding hardware. Significant market penetration of mmWave-based systems is anticipated to meet the increasing data rate demand of future WPAN. According to the Telecommunication Industry Association (TIA), spending in the U.S. telecommunications industry rose to an estimated $856B in 2005 and is expected to reach $944B in 2006. In 2005, wireless devices revenue reached to $15B while wireless services revenue rose by $118B.

***Technical Barrier to the Innovation*:** An appropriate channel model for mmWave-based wireless systems that contains "Spatial-Temporal" information is needed to properly evaluate the performance of future wireless personal area networks. Uncertainties in spatial distribution of RF energy around a receiver make it difficult to compare various designs of mmWave-based systems employing directional (or smart antennas) at the receiver (and/or transmitter). Standard bodies such as IEEE802.15.3c require an appropriate channel model to make informed decisions about proposed systems designs or recommended modifications. Lack of a correct standard model could lead to uncertainty in the performance evaluation process and eventually possibility of error in the final selection.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Obtaining the spatial-temporal information for an indoor channel requires accurate signal measurement with high gain directional antennas for various number transmitter-receiver directions, locations and indoor environments. Spatial information is inherently 3-dimensional but appropriately measured 2-dimensional information could also provide useful data.

***Potential Solutions to Measurement Problem*:** R&D to develop test scenarios that closely resemble the indoor application environment; developing accurate/effective measurement techniques that results in the observation of the spatial distribution of RF energy around the receiver as well as temporal distribution of the multipath signal; in-depth analysis of the measurement data to extract a relevant model applicable for systems with non-omni-directional antennas at the receiver (and/or transmitter).

Case Study – Measurement Needs

***Technology at Issue*:** Network and System Security Levels

***Submitter*:** Joan Hash

***Technological Innovation at Stake*:** A means for real-time network monitoring to detect changes in system vulnerability. This could be accomplished in part through an introduction into the marketplace of specifications, standards, and reference data as methods for the characterization of the security of networks and systems. Though there is an increasing dependence on systems to process sensitive information and to control vital processes, there is no standard way of assessing and communicating the security of a system or network. The threats against information systems are constantly evolving. Therefore, there is a need for a means to consistently measure and report the state of the security of such systems.

***Economic Significance of Innovation*:** Information technology helps form the backbone of the Nation's critical infrastructure. System breaches and disruptions translate into downtime, productivity losses, financial losses, and the disruption of mission critical services and daily operations. According to the CSI/FBI Computer Crime and Security Survey, organizations surveyed estimated the total cost of cyber security breaches to be more than $130M in 2005 alone. This only represents costs to respondents and therefore is a mere fraction of actual costs across the Nation. With major government services and operations moving to the Internet and with the aggressive move to e-Government, measurements related to information technology infrastructures speak directly to the ability to protect the safety and economic health of the country. A standard way of assessing and reporting system and network security is key to addressing security issues before they result in incidents leading to great financial loss or significant instability in the nation's critical infrastructure.

***Technical Barrier to the Innovation*:** Barriers to creating standard security levels include lack of (1) agreement on a representative set of measurable network/system characteristics; (2) corresponding reference data; and (3) means to use this taxonomy and set of criteria to characterize systems of various forms and functions and allow for meaningful comparisons.

***Stage of Innovation Where Barrier Appears*:** R&D, Production, and End Use

***Measurement-Problem Part of Technical Barrier*:** One barrier is agreement on how to specifically express the problem and a set of measurable network/system characteristics that taken together with reference data (also to be derived) are indicators of the security status of the system/network.

***Potential Solutions to Measurement Problem*:** A combination of consensus building workshops and research could be used to develop the taxonomy and reference data sets necessary to express security levels for networks and systems upon which specifications and standards could be based.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** 3D Shape Searching

***Submitter*:** Sandy Ressler and Afzal Godil, NIST

***Technological Innovation at Stake*:** The ability to search (and reuse) databases containing spatial, or geometric, information, such as manufactured parts, human organs, or spatial environments.

***Economic Significance of Innovation*:** Spatial information, which graphically displays details (such as the design of parts, the layout of rooms and buildings, and the relationship of human organs), is currently only retrievable by skilled specialized experts. The ability to search for 3D objects, easily and intuitively, will open up vast archives of spatial information, and make them more useful and valuable. Thus, this could be conceived as a Google-like search engine, but using 3-D information, not textual information. The potential impact is enormous and infrastructural, with large social benefits and wide applicability. For example in health care, a cardiologist could query a database of heart shapes for certain types of abnormalities resulting in information to help diagnosis. As another example, manufacturing processes, which are heavily dependent on shape information, can be significantly improved and optimized in a faster and cheaper way by enabling CAD/CAM/CAE systems to use shape searching to reuse parts and processes in designs and models. The economic impact of this alone is estimated to be over $1 billion.

***Technical Barrier to the Innovation*:** Lack of validated, robust data bases with shape data for a variety of applications for the research community. Existing shape searching research projects work with very small and limited databases that at best reflect the needs of only one type of application.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Evaluation algorithms for 3D search systems and user interfaces

***Potential Solutions to Measurement Problem*:** Create reference databases and algorithms that are easily accessible and available. Note that these types of databases are not simply data but are also the programs and interfaces needed to access, evaluate and modify the databases as well.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Search

***Submitter*:** Ian Soboroff

***Technological Innovation at Stake*:** Advanced search technology is needed to handle emerging content (blogs, wikis, digital video, chat) as well as new domains (searching email, organizing desktop files). Search technology kept the World-Wide Web usable as it grew to billions of pages. Emerging media offer new capabilities for internet users, but until we can search them their usefulness is limited. For example, now that email is a critical business tool, search, spam filtering and automatic foldering are increasingly essential capabilities.

***Economic Significance of Innovation*:** Effective search technology dramatically increases productivity of researchers, workers, and consumers by helping them find what they need quickly. 5.1 billion searches were conducted using web search engines in December 2005, up from 3.3 billion a year earlier (Nielsen//NetRatings). 70-80% of users use search engines to find sites. Internet advertising is a $10-12 billion per year industry, with search advertising is accounting for 40% of those revenues.

***Technical Barrier to the Innovation*:** As new content technologies such as blogs, digital video, integrated messaging become popular, users want to be able to search them as easily as they now search the web. Existing search systems, proven in existing environments, are not effective for searching new types of content because they require new assumptions and new search algorithms. For example, initial desktop search products based on web search technology were widely perceived as ineffective. People search differently on the web, in news, in blogs, in their own email, and among their own files. Until we understand the structure of new content, how people use it, and how they want to search it, we can't measure how well search works. Measurement of search effectiveness is critical to developing, improving, and deploying search systems.

***Stage of Innovation Where Barrier Appears*:** R&D, Marketplace, End Use

***Measurement-Problem Part of Technical Barrier*:** Measurement of search effectiveness requires test data collections and metrics that reflect the users' needs. Common metrics include precision and recall of a list of search results. It is difficult to measure search effectiveness as information collections become larger, new applications emerge, and searching tasks become more complex. Without appropriate performance and accuracy metrics and test collections, it is difficult to improve search technology (R&D), market (marketplace) or reliably choose a search system (end use). Developing test collections and metrics for new domains requires understanding of the medium, how it is used, how users want to search it.

***Potential Solutions to Measurement Problem*:** Test collections, collection construction methods, evaluation methodologies, metrics designed for new media and matching how users search them, and an open environment for sharing results.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Intelligent Machine Systems

***Submitter*:** James Albus

***Technological Innovation at Stake*:** Intelligence can be defined as the ability to accomplish complex goals in dynamic, uncertain, and possibly hostile environments. Intelligent machine systems are those that can perform complex missions with limited human oversight. The fundamental processes that will enable machines to act intelligently, independently, and reliably are understood, at least in principle. There is a growing consensus that major advances in intelligent machines will occur in the next 5 to 15 years. Intelligent machine systems may become a defining technology of the 21^{st} century.

***Economic Significance of Innovation*:** The development of intelligence in machine systems for manufacturing, transportation, construction, agriculture, mining, and health care will dramatically improve productivity, increase quality, reduce costs, and accelerate the rate at which goods and services can be produced. Intelligent weapons systems will revolutionize warfare. Truly intelligent machine systems will almost certainly have a profound impact on the modern socio-economic system. An economic impact study is currently being conducted to estimate the potential impact of intelligent machine systems technology in the manufacturing and construction sectors – results are expected to be available in late Spring 2006. Similar studies have been performed by DOD and DOT.

***Technical Barrier to the Innovation*:** The most advanced intelligent machine systems may approach or exceed human performance, and might become comparable in complexity to the human brain. System validation of such complex systems will be a monumental challenge. There are no standard metrics or methodologies for measuring the performance of either components or systems. The very definition of intelligence is not well established, and methods for measuring the performance of intelligent systems are ad hoc and rudimentary.

***Stage of Innovation Where Barrier Appears*:** R&D, Marketplace, and End Use

***Measurement-Problem Part of Technical Barrier*:** Measuring the functional performance and degree of autonomy of intelligent systems will require new metrics and methods for testing. Quantitative methods will be needed for measuring performance under realistic environmental conditions. For example, intelligent automotive systems will require testing under realistic weather conditions and traffic situations, while robots for fire fighting and urban search and rescue will require testing their ability to maneuver in burning or collapsed buildings, and to recognize and rescue victims.

***Potential Solutions to Measurement Problem*:** R&D is needed to develop metrics, performance measures, environments and artifacts, and test methodologies for intelligent systems and components.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Next Generation Electronic Product Accessibility

Submitter: Sharon Laskowski and Charles L. Sheppard

Technological Innovation at Stake: Approaches to user interface design that allow broader accessibility through alternate interface devices for people with disabilities and for environments that require flexible access. This includes not only static plug-and-play accessibility, but also independent rendering of user interfaces for adaptation and interoperability with new interaction modalities, such as large or small screens, keyboards, tablets, Braille devices, embedded devices, gesture, natural language, and speech interaction.

***Economic Significance of Innovation*:** First, there is a societal benefit: products that are designed to adapt to user needs and be controlled with alternate interface devices are less expensive, easier to use, and accessible for more people. Public devices such as ATMs and information kiosks could also be more accessible. Without this innovation, people with disabilities have to rely on devices that are especially designed for them at higher cost and with limited choices. Second, there is a long-term economic benefit to industry. Electronic products, such as handheld devices, cell phones, and other smart embedded devices are focused primarily on the youth market; the aging and disabled populations have been largely ignored. The oldest baby boomers are now turning 60; there is an ever growing set of aging consumers with large discretionary income, and, therefore, a much larger customer base for electronic devices that are easily accessible by the aging and disabled populations. There is also a market for devices that can be operated in special situations such as noisy or hands-busy environments. Finally, software reuse and third-party specialized interfaces would be possible through agreed upon standards. So, why isn't industry doing this? The primary reasons are: initial cost of changing of design and marketing strategies and hiring experts, reluctance to agree to interoperability standards because of a fear of loss of branding, and a traditional approach of selling to the youth market while not recognizing the ever growing set of tech-savvy aging and disabled populations. These are similar reasons to those used for creating Section 508 to push industry to design for IT accessibility.

***Technical Barrier to the Innovation*:** Currently, industry does not have an agreed set of user interface interoperability requirements and measurement methods for these next generation devices. Without the standards to support more interoperable, universal accessibility and control for different user interface renderings, product developers will continue to build products that, in most cases, cannot be made accessible after market.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Measurement of accessibility and ease of use for different populations and contexts through evaluations of the human device interaction combined with measurement of degree of interoperability will enable designers to maximize accessibility and adaptation. Without this informed guidance, large segments of society will find it difficult or impossible to directly and easily use these new products. The challenge is to get industry to work together to design for accessibility and then to create an infrastructure of design guidance and standards and measurements to support adaptation and interoperability.

Potential Solutions to Measurement Problem: Involve forward looking product developers and accessibility experts in consensus standards development and in creation of measurement and design guidance.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** HCI in Ubiquitous Computing

***Submitter*:** Sharon J. Laskowski

Technological Innovation at Stake: The innovation is seamless, non-invasive, and effective human-computer interaction (HCI) for ubiquitous computing applications (off-the-desktop, next generation interactive systems) with new types of interaction, and collaboration among greater numbers of users. To achieve Weiser's vision[2] of seamless cohabitation of the world by humans and computers, such systems must be truly woven into everyday work and play. This involves looking beyond the typical aspects of usability for tasks and considering the human experience in the human computer interaction (HCI).

***Economic Significance of Innovation*:** Ubiquitous computing will enable innovative products and totally new services to be developed. There will be "smart" industrial products with integrated information processing capacity, electronic identities that can be remotely queried, embedded sensors for detecting the environment, and new forms of user interaction and control.

***Technical Barrier to the Innovation*:** There are societal challenges introduced by ubiquitous computing characterized by dependence on technology, control over information linked to objects, and privacy. Successful deployment depends, in part, on HCI designed with the context in mind so that users find the applications useful and non-invasive. Designs that do not fit the social context-of-use will fail in the marketplace. Hence, identification of the requirements and design principles becomes critical for acceptance of ubiquitous applications.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The complexity (multi-modal, collaborative, involving large amounts of information) of these systems makes it difficult to establish common user interface design criteria and evaluation techniques needed to create seamless, useful interfaces. Many systems are based on devices where interaction depends on speech, gesture, physical interactions, as well as traditional graphical and text-based user interfaces. New HCI evaluation methodologies, which go beyond traditional usability metrics, are needed to measure this new technology with greater emphasis on values, emotion, privacy, trust, and other social aspects that ubiquitous applications exhibit.

***Potential Solutions to Measurement Problem*:** A framework of metrics and evaluation methods, validated through case studies of research systems, can provide an environment for researchers to share and learn from each other's evaluations. This will require a good deal of experimentation and measurement by the research community. Such an approach can result in validated metrics, effective discount evaluation techniques, and design guidelines that can then be put to use to improve the human computer interaction of these systems. See http://www.itl.nist.gov/iad/vvrg/newweb/ubiq for additional details and references.

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2 Weiser, M., "The Computer for the 21st Century," *Scientific American*, 265, (1991), pp.94-104.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Machine recognizable, and identifiable, digitally coded speech

***Submitter*:** Vincent Stanford

***Technological Innovation at Stake*:** Advanced Digital Voice Coder (vocoders) with machine intelligibility, identifiability, and low bit rates. Digital vocoders reduce speech to digital bit streams with rates as low as 600 bits per second, but accuracy of speech recognition, and voice biometrics, vary greatly with different vocoders. This issue will impact the effectiveness of homeland security voice communication systems, and voice communication systems in general.

***Economic Significance of Innovation*:** This is a medium technical risk research area with potential for high impact in improving utility and clearer quality of machine recognizable speech produced from digital communication systems for first responder, law enforcement, and other voice system user communities. This will allow improved communication security in the field, and recognition-based services such as voice access to law enforcement wants and warrants databases, or other secure data controlled by speaker identity. There is also high potential for improved ability to deploy new generation voice communication systems faster and with greater system assurance in shorter time spans.

***Technical Barrier to the Innovation*:** Recent research shows that the GSM (Global System for Mobile Communications) vocoder increases speaker identification error rates by eight to ten times. This is not yet quantified for other widely used vocoders such as Linear Predictive Coding (LPC), Code-Excited Linear Predictive (CELP), and Mixed Excitation Linear Prediction (MELP), but it strongly suggests problems will be encountered in digital voice systems as we attempt to add machine recognition services.

Stage of Innovation Where Barrier Appears: R&D and End-use

***Measurement-Problem Part of Technical Barrier*:** Currently human listeners are required to measure intelligibility, which is cumbersome and expensive. Metrics that predict human and machine speech recognition and speaker recognition error rates are needed facilitate improving these systems. Automated metrics and technology evaluation methods must be developed to assure voice communication systems are compatible with machine recognition systems for speech and speakers. This will help push the state-of-the-art to the reliability levels needed by first responders systems and for commercial products.

***Potential Solutions to Measurement Problem*:** Develop metrics for speech signals that measure and predict accuracy rates of speaker identification, and speech recognition systems, under a variety of voice transcodings and noise conditions. These must include advanced measurements for signal-to-noise, and issues like reverberation and multipath, and their interaction with existing voice coding algorithms and channel characteristics. Work with first responder community to better understand the metrics needed; and in collaboration with research community, perform evaluations, and to push the state-of-the-art algorithms into reliable field-deployed systems. Evaluations based on standard reference data and measurement algorithms are needed to understand how to develop reliable and accurate voice communication systems, and needed recognition services based on them.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Checkpoint identification of humans

***Submitter*:** Jonathan Phillips & Vincent Stanford

Technological Innovation at Stake: Ability for automated identification systems to recognize particular humans in unconstrained environments, like airports, security checkpoints, and in other security applications based on iris, face, and gait, in a variety of modes, including video, infrared, millimeter wave, and other multispectral bands

***Economic Significance of Innovation*:** This is a long-term research area in a family of interlocking biometric identification technologies with potential for high impact in improving national security. The benefit of improved homeland security is potentially very high. Immediately after the 2001 terrorist attacks, there arose a false expectation that face recognition systems could identify terrorists in crowded areas. Several airports implemented, and soon removed, these systems after it became obvious that they were not effective. Successful systems could help rapidly identify terrorists and others posing a national security threat at borders, at war zones abroad, military bases, and high-profile facilities and buildings.

***Technical Barrier to the Innovation*:** Significant barriers include the lack of large calibrated data sets to support multimodal research activities in government, industry, and academia. Particularly, research avenues involving sensor fusion demand large data sets. Basic pattern recognition algorithms, and computer vision must be made robust with respect to signature variations caused by environmental variations due to illumination, angles of presentation, and resolution changes due to field of view. Semantic interpretation algorithms must be developed and calibrated in order to infer hostile intent if it is present. This will require new measurement and characterization of the primary signatures.

Stage of Innovation Where Barrier Appears: R&D and Production

***Measurement-Problem Part of Technical Barrier*:** The human identification problem will require a combination of metrics that operate on individual stages of the problem; e.g., face recognition and voice recognition both offer promising avenues of research, and a sensor fusion of the two may be even more powerful because of the independent information contained in each channel. System level metrics must be developed for multispectral measurements and their performance in combination. Some of the open avenues of investigation include, face recognition from video, iris measurements, fingerprints, and speaker identification from voice. Also standard data sets taken under varying conditions will have to be employed as part of standard benchmarks and metrics to assess the performance of algorithms using agreed to metrics yet to be developed.

***Potential Solutions to Measurement Problem*:** Work with the biometric R&D community to understand feature/signature extraction, standardize performance metrics, and identify relevant data resources that can be used to facilitate algorithm development and evaluation.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Motion Imagery Quality

***Submitter*:** Charles Fenimore

Technological Innovation at Stake: Next generation motion imagery systems for intelligence analysis and surveillance for Homeland Security, government surveillance, advanced video search and retrieval, and commercial security.

***Economic Significance of Innovation*:** This is a high risk research area with potential for high impact in Homeland Security by improving the quality of intelligence and surveillance information derived from video images for national security applications. This technology could assist the intelligence community in detecting and recognizing security risks in many areas including airports. There is also high impact in broader commercial applications for next generation security and policing imagery systems.

***Technical Barrier to the Innovation*:** One major barrier is the inability to assess imagery quality and image interpretability of motion imagery. There is general agreement that emerging surveillance systems do not perform very well and produce imagery that is often not interpretable, and therefore not useful as an intelligence tool. The dynamic nature of motion imagery contributes to the difficulty in understanding and quantifying effects of factors, such as scene complexity, color, camera motion, distance, and resolution; these factors need to be understood alone as well as in combination. Much research and development is still needed to improve the level of accuracy and reliability to meet the requirements of the intelligence community and for commercial search and security systems.

Stage of Innovation Where Barrier Appears: R&D and Production

***Measurement-Problem Part of Technical Barrier*:** Although there is a scale for measuring still images, there is currently no measurement scale or metric to quantify motion imagery, in particular in applications that require detecting, identifying, and tracking objects and people. Currently, even measurement of image complexity and motion in a high resolution videoclip is not reliable. Establishing the appropriate metrics and evaluation methods is critical for quantifying motion image quality to help push the state-of-the-art to the reliability level needed by the intelligence community and by commercial video imagery systems. Research in measuring performance has begun, but needs greater focus to accelerate this technology. Metrics are needed, for example, to characterize the amount of motion and complexity of imagery in video, to measure motion image quality, interpretability of images, and effects of video compression on motion image perception.

***Potential Solutions to Measurement Problem*:** Perform further research and evaluations, in collaboration with the intelligence community, to better understand the metrics needed in intelligence analysis applications. In collaboration with research community, perform evaluations to push the state-of-the-art towards reliable, commercialized systems. Evaluations are needed to understand the appropriate test data, methods, and metrics for applications to measure accuracy of a new class of video retrieval and motion image systems. Develop motion imagery quality scale, metrics, test materials, and methodology.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Multimodal, context aware, and user sensitive interfaces

***Submitter*:** Vincent Stanford

Technological Innovation at Stake: Direct human-to-computer communication on human terms would powerfully enhance productivity. Inherently multi-modal, it involves speech, gesture, gaze, and even facial expression. Identifying speakers from voice and video, what they say, who they look at, gestures they make, and who responds, are fundamental to human context aware human-machine interfaces.

***Economic Significance of Innovation*:** This research could have high impact in a family of interlocking technologies important to national security, human computer interaction, video processing, information indexing, and information retrieval applications. Successful user sensitive interfaces would lead to more efficient and natural control of computer systems and would require less knowledge of the technology by the user. These technologies support recognition in still images, video, spoken language, of people and objects, and of information retrieval. This would also enhance knowledge-worker productivity and work done in groups. The strong EU programs in this area suggest inaction by the U.S. research establishment risks ceding this critical area to our economic competitors.

***Technical Barrier to the Innovation*:** Numerous pattern recognition and sensor fusion algorithms must be further developed to support necessary semantic analyses of human activities for this innovation. All of the necessary detection and classification algorithms that must function and be combined in sensor fusion for effective annotation of human activities are in the early stages of development. Automated speech recognition, speaker identification, face identification, gesture recognition, and gaze tracking are component technologies that require support from more basic pattern recognition capabilities such as source localization from microphone arrays and sensor fusion with face localization and recognition.

Stage of Innovation Where Barrier Appears: R&D

***Measurement-Problem Part of Technical Barrier*:** The multimodal context-aware interface problem requires numerous metrics that operate on the detection, localization, and classification stages of the problem, and also system level metrics. For example, if a system is to respond to a query from a person in a meeting space, it must recognize the person, the spoken words, and form a data base query from the words. All of these steps have their own error rates, and the metrics must illuminate the actual causes of given errors. Standard data sets are needed to assess algorithm performance, using recognized metrics.

***Potential Solutions to Measurement Problem*:** Work with the R&D community to standardize performance metrics and identify relevant data resources that can be used to facilitate algorithm development and evaluation.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Machine Tool Accuracy

***Submitter*:** M. Alkan Donmez / Hans Soons

***Technological Innovation at Stake*:** Enhanced machine tool accuracy allows for the faster and more reliable manufacture of ever more complex part geometries at tighter tolerances and lower cost, enabling product innovations. Current approaches to improve machine accuracy are reaching technical and economical limits.

***Economic Significance of Innovation*:** While the machine tool industry is relatively small--U.S. purchases and shipments in 2005 totaled $5.8 B and $3.2 B respectively--it has a highly-leveraged impact on the U.S. economy and national security. A study credits advancements in manufacturing technologies, machine tools specifically, to benefits of nearly $1 trillion to the U.S. economy over 1994-1999. These benefits resulted from gains in productivity, declines in inventory requirements, and manufacturing-related product improvements for price, quality, performance, and energy efficiency. Accuracy improvements of machine tools have been a key factor in realizing these benefits. U.S. machine tool users are facing intense global competition while having to address more complex parts, closer tolerances, smaller batch sizes, shorter time-to-market, and higher cost of skilled machinists. Competitiveness requires machine tools whose accuracy is known and "guaranteed" for a wide variety of tasks and operating conditions.

***Technical Barrier to the Innovation*:** The ability of a machine tool to produce parts to specification is to a large extent determined by the accuracy of the path of the cutting tool relative to the part. Since the 19th century, machine tools have relied on measurement systems embedded in each axis. There is, however, a gap between the accuracy of these measurement systems and the accuracy of the tool path. This is because the measurement systems do not detect straightness and angular errors in slide motion and errors in axis alignment. These errors cause a high variability in machine accuracy due to their complex dependency on the machining task, and their sensitivity to thermal loads, mechanical loads, and the effects of wear and collisions. As a result, machine tool users have to accept large uncertainties in part accuracy, which in turn requires major expenditures on part inspection and process tuning to realize requested specifications.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** A system for the direct measurement of errors in the position and orientation of the tool relative to the workpiece would yield fundamental improvements in machine accuracy that are only limited by our ability to measure and correct. This enables new machine designs, such as walkers that bring the tool to the workpiece. The challenges to realizing this metrology system are however significant. It must operate reliably under adverse machining conditions (vibrations, coolant, and chips), be unobtrusive, and be able to accommodate high contouring speeds.

***Potential Solutions to Measurement Problem*:** In dimensional metrology, advances have been made on systems for the direct measurement of position of a probe or artifact in space. Examples include 3D laser trackers, laser alignment, laser trilateration, photogrammetry, volumetric interferometry, and micro-GPS. These technologies may be applied to tool-workpiece positioning. More feasible near-term solutions are in-situ inspection of machined parts, yielding results that are not affected by the errors of the machine, and fast calibration of machine tools.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Advanced Machining Processes for Manufacturing

***Submitter*:** Richard Rhorer

***Technological Innovation at Stake*:** In order for U.S. manufacturers to continue competing globally, efficiency must continue to rise. Machining processes are a key factor in this hunt for efficiency. By increasing machining speeds to the highest practical level, time is saved and costs are reduced. Research into innovative machining processes is ongoing within universities and industry but requires the precise measurement of temperatures in the very small cutting/shear zone of metal cutting processes.

***Economic Significance of Innovation*:** Both innovation of new processes and optimization of old processes with innovative new approaches are essential to maintain the significant role that the machining industry plays in the U.S. The economic impact of improving machining processes is large. For example, the cost of labor plus overhead for operating machine tools in U.S. factories has been estimated to be on the order of $200B. By providing the measurement tools needed to measure cutting temperatures accurately and aid in improving the processes, it is conceivable that the cutting speeds can be increased by an average of 1% in approximately 10% of the processes, or an economic benefit on the order of $200M.

***Technical Barrier to the Innovation*:** In machining, the maximum cutting speed is limited by the temperature generated at the tool tip, and measuring the cutting temperature is a vital step in obtaining the optimum speed for any particular machining process. Temperature measurements also are essential for verifying or validating modeling and simulation methods employed in the quest for improved efficiency.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Measurement of temperature in the cutting zone of a machining process is challenging because the temperature gradients are high, and therefore, extremely high spatial resolution (on the order of one micrometer) is needed to map the temperature in the tool and work piece. Further, the machining process is highly dynamic (strain rates of 10^3 s^{-1} or higher) requiring high temporal resolution. A practical barrier in measuring temperatures in machining experiments is the difficulty in obtaining a clear view of the very narrow shear zone (less than one mm). Therefore, the challenge is how to measure the temperature fields in a small (approximately 1.0 mm square) zone with gradients of 1000 degrees C through the zone.

***Potential Solutions to Measurement Problem*:** The most promising methods for making precise temperature measurements in the shear zone of machining processes are those employing state of the art infrared or thermal cameras.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue**:** Machine Tool Dynamics

Submitter**:** A. Donmez

Technological Innovation at Stake**:** Determination/estimation of machine tool dynamic behavior is a key enabler for high-speed machining. High-speed machining is only possible if one can avoid unstable parameter space associated with the machine tool/cutting tool/workpiece system. Fast and accurate determination of frequency response functions (FRFs) of various machine tool - cutting tool pairs will allow the introduction of new process optimization tools to maximize machining process efficiency and minimize costs.

Economic Significance of Innovation**:** High-speed machining of aluminum and titanium amounts to a significant percentage of manufacturing costs in the aerospace and defense industry. Pressures on manufacturing industry to achieve faster, better, and cheaper production are creating conditions where quick dynamic performance determination is critical. Increasing the material removal rate by only a few percent without creating unstable cutting can save millions of dollars in the production of aerospace and defense related parts. For example, Boeing uses about 1000 machine spindles per year. Chatter prevention has been shown to improve typical spindle life from 40 hours to 450 hours in extreme applications.

Technical Barrier to the Innovation**:** Researchers are investigating new methods where information on dynamic behavior can be obtained using a combination of predetermined dynamic performance information for the components of the spindle/tool holder/cutting tool assembly (receptance coupling approach). A significant barrier to this approach is the determination of rotational frequency response at the interfaces of these components. The traditional method to determine dynamic behavior is to attach the cutting tool to the machine spindle using an interface device (tool holder), carry out impact tests, and measure the linear acceleration response at the tip of the tool. By correlating the response to the excitation force, a frequency response function at the tool tip is obtained and used for predicting stable cutting regimes. However, such a determination requires sensitive and complex measurements to be taken every time a tool change operation is performed. It is a very costly and difficult process and is therefore not widely used by industry.

Stage of Innovation Where Barrier Appears**:** R&D

Measurement-Problem Part of Technical Barrier**:** Determining rotational frequency response at machine interfaces requires accurate and traceable dynamic angular displacement/velocity/acceleration metrology as well as robust methodologies for estimating uncertainties associated with rotational and linear FRFs and propagation of those in calculating dynamic performance of the spindle/tool assembly.

Potential Solutions to Measurement Problem**:** One part of the solution is for NMIs to develop a calibration system for angular accelerometers that establishes the traceability chain for such measurements. University researchers are continuing their work on receptance coupling theory and application and can incorporate measurement methodologies developed by NMIs.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** Measuring and Modeling Dynamic Strain for Machining Processes

***Submitter*:** Richard Rhorer

***Technological Innovation at Stake*:** Maximized machining process efficiency and innovation of new machining processes for U.S. manufacturing.

***Economic Significance of Innovation*:** Manufacturing enterprises of the future will undoubtedly rely heavily on modeling and simulation in order to ensure process quality before committing resources to hardware. The economic impact can be significant. For example, the cost of labor plus overhead for operating machine tools in American factories has been estimated to be on the order of $200B. If modeling and simulation can contribute to increasing the efficiency of new processes by only 0.5%, and old processes are replaced at a rate of 10% per year, the economic benefit in one year could be estimated to be on the order of $100M per year.

***Technical Barrier to the Innovation*:** The predictive modeling and simulation of machining processes rely on the ability to measure strains and associated stresses in the material being machined. The technical barrier to obtaining these strain and stress measurements results from the complexity of the machining process, which involves: large strains (over 200%), very high strain rates (greater than 10^3 per second), high temperatures (1000 degrees C), and high heating rates (10,000 degrees C per second or higher). Traditional material testing does not provide the necessary properties under these conditions.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The measurement problem is simultaneously measuring the force, deformation, and temperature of a sample where the test lasts on the order of 100 microseconds.

***Potential Solutions to Measurement Problem*:** Since the 1950s the most common approach to determining dynamic properties of materials at high strain rates has been the Split Hopkinson Pressure Bar, also called the Kolsky Bar. NIST has contributed a method of pulse heating the samples to provide the capability of measuring dynamic properties at elevated temperatures. Recent advances of computer technology and the innovations of high speed digital video cameras (100,000 frames per second or faster) have opened a new approach to measuring the response of a sample in the Kolsky Bar apparatus. There is a significant potential for improved measurements of mechanical behavior using the Kolsky Bar as a result of the application of high speed thermal and visible light cameras.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Economically Viable Fuel Cells

***Submitter*:** A. Donmez, E.Stanfield, D.Stieren

***Technological Innovation at Stake*:** The fuel cell is promising and vital component of the future hydrogen economy. However, issues of price, driven appreciably by manufacturing costs, are hampering the potential of this innovation.

***Economic Significance of Innovation*:** America's future well-being is linked to the availability of clean, secure, and sustainable energy. A major milestone of the President's Hydrogen Fuel Initiative is to develop hydrogen technologies to the point that U.S. industry can make a commercialization decision about hydrogen fuel cell cars and fueling systems by 2015 so that these vehicles can begin to penetrate the consumer marketplace by 2020. Manufacturing accounts for a significant portion of fuel cell component and system costs, and quality control issues are significant drivers for overall cost reduction, especially as manufacturing scales up to high volumes. In the recently published DOE Roadmap on Manufacturing R&D for the Hydrogen Economy, it was indicated that the present cost of direct hydrogen fuel cell power systems was about $ 3,000 /kW. It is also estimated that based on a large scale production of 500,000 units per year the cost would drop to $ 108 /kW. The DOE Roadmap also states that "the major factor for the difference between today's cost and projected cost is the cost of manufacturing at today's production rates of hundreds of power plants per year compared to projected mature production process costs for 500,000 units per year."

***Technical Barrier to the Innovation*:** To strengthen the quality control of fuel cell manufacturing, there is a broad need to advance the fundamental understanding of the role of fabrication, metrology, and process control technology with respect to the performance characteristics of fuel cells, and to develop a knowledge base of fundamental, precompetitive manufacturing process technologies, reliable measurements, and standards for fuel cell manufacturability.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** Measurements of physical, electrical, and chemical properties of fuel cells and their components, made in line, during the manufacturing process, are necessary to address fuel cell quality control issues. Currently identified areas in need of this type of metrological support are bipolar plate design and fabrication, characterization of membrane electrode assemblies, stack assembly, and overall fuel cell performance characterization.

***Potential Solutions to Measurement Problem*:** Addressing the metrological aspects of quality control for fuel cell production will introduce deterministic manufacturing concepts into fuel cell manufacture. Development and implementation of inline, real-time measurements of mechanical, electrical, and chemical properties of the fuel cell and its components would advance the state-of-the-art in fuel cell manufacturability by providing fundamental correlations between component fabrication tolerances, assembly tolerances, and overall fuel cell performance.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** High Accuracy Dimensional Metrology for Manufacturing

***Submitter*:** T. LeBrun

***Technological Innovation at Stake*:** Technological progress in many high-technology manufacturing industries continually pushes the limits of accuracy required in dimensional measurement. Diverse needs ranging from the manufacturing of next generation semiconductor devices to the development of nanotechnology-based products for health care or advanced computing require dimensional measurements with better accuracy than is currently achieved anywhere in the world.

***Economic Significance of Innovation*:** Improved dimensional metrology allows manufacturers to maintain higher standards and lower costs, by enhancing repeatability and throughput of manufacturing processes, thus increasing manufacturing yield and profitability. Improved metrology also fosters the creation of new products such as high-density memory, that require ever higher densities of components to be fabricated in small devices. These all contribute to competitiveness, and generate economic benefits for U.S. industry.

***Technical Barrier to the Innovation*:** Manufacturers of leading edge products in the semiconductor and nanotechnology areas, among others, need access to better dimensional measurements than are currently available. Many of these manufacturers use NIST standards and measurement services to calibrate their key measurement tools for production and development. In some highly competitive areas where NIST Standard Reference Materials (SRMs) are just keeping up with industry needs, the dominant uncertainty in the SRMs result from the limits in NIST's ability to measure length — even when using a tool that is one of the most accurate in the world.

***Stage of Innovation Where Barrier Appears*:** R&D (primary), Production (secondary)

***Measurement-Problem Part of Technical Barrier*:** The best dimensional metrology tools in the world are generally limited by two problems: the uncertainty in the index of refraction of air (which changes the wavelength of light and thus the scale of the measurement), and the ability to accurately and reproducibly measure the position of a line to within nanometers.

***Potential Solutions to Measurement Problem*:** Develop a next-generation dimensional measurement instrument to replace the current facility (the NIST linescale interferometer). The new instrument should incorporate vacuum beam paths for refractive index compensation and CCD imaging paired with a traditional slit-scanning photomultiplier for nanometer-scale line position measurement.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Integrated Circuit Overlay Metrology

***Submitter*:** Rick Silver

***Technological Innovation at Stake*:** As the critical dimensions of key attributes in advanced semiconductor devices for the worldwide electronic products market get smaller and smaller, measuring the relative alignment of these features is becoming increasingly difficult. New challenges are arising, such as maintaining higher accuracy requirements and even the fundamental ability to resolve such small features. Meeting these challenges will allow the development of more powerful, more reliable, and/or less expensive electronic products.

***Economic Significance of Innovation*:** The U.S. industry has held a preeminent position in the design of advanced and next generation semiconductor devices as well as the instrumentation used to manufacture them. For U.S. industry to maintain a leadership role in the continued exponential shrinkage of semiconductors, as well as in their production with yet lower cost per function, significant investment and R & D in manufacturing metrology is required. The exponential growth of semiconductor production has created very significant market segments with technological leadership from the U.S. Even the smallest improvements in measurement innovation and manufacturing process control can yield millions of dollars in return. This economic sector is so advanced and automated that clever solutions and advances can have very significant and measurable effects.

***Technical Barrier to the Innovation*:** The sizes and placement of features on the mask must be measured accurately in order to obtain acceptable manufacturing yields and profit levels. To accurately provide robust measurement and process control capabilities, accurate optical measurement techniques, tool alignment and electromagnetic scattering models, which simulate the imaging process, are needed.

***Stage of Innovation Where Barrier Appears*:** R&D (primary) and Production (secondary)

***Measurement-Problem Part of Technical Barrier*:** There are several challenges in measuring optical targets composed of features nearly $1/10^{th}$ the size of the measurement wavelength used. These challenges include: aligning the optics, defining algorithms, and developing CCD measurement capabilities with better than 1 nm resolution and accuracy. Doing this in a way to enable high throughput and accuracy requires pushing optical techniques to new levels.

***Potential Solutions to Measurement Problem*:** Implement new high resolution scatterfield microscopy techniques to the overlay wafer measurement domain. Quantify the effect of measurement uncertainty on device yield and process control.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** SEM Integrated Circuit Metrology

***Submitter*:** Andras Vladar, Michael Postek

***Technological Innovation at Stake*:** Integrated circuit (IC) technology is a key enabler for the worldwide electronic products, is the economic engine for many other industries and provides the basis for unfolding information technology. IC manufacturing faces new challenges in maintaining the pace of making new, faster and more powerful devices. The current dimensional metrology methods for IC manufacturing barely suffice for production requirements, and unless new methods come into existence, significant advances may be hindered.

***Economic Significance of Innovation*:** The computing performance of integrated circuits has been growing exponentially over the last decades, and this growth has been coupled with falling IC prices. This pervasive technology has created one of the largest market segments of the world economy, improved the standard of living worldwide and led to new methods and technologies in virtually every segment of human activity. The importance of these dimensional measurements has been highlighted by the fact that even only 1 nm improvement in the control of the processes leads to hundreds of millions of dollars saved.

***Technical Barrier to the Innovation*:** IC technology needs reliable l metrology methods that accurately report changes in the size and shape of the circuits during the various production steps. The sizes and placement of these features on the wafers must be measured accurately in order to manufacture integrated circuits within the specifications. These measurements tell the technologist that the wafers need to be reworked or can indeed proceed in the next, irreversible step in the technology production.

***Stage of Innovation Where Barrier Appears*:** R&D (primary), Production (secondary)

***Measurement-Problem Part of Technical Barrier*:** The tolerances of IC wafer features, combined with the uncertainties of their measurements, present a significant problem, which at this point has no complete solution.

***Potential Solutions to Measurement Problem*:** Verify and improve the performance of existing scanning electron microscope (SEM) imaging and measurement methods and models. Improve wafer feature measurement techniques. Assess the effect of measurement uncertainty on IC device performance. Develop SEM-based traceable measurement methods. Accurate standards and their proper application need to be developed to ensure the continuing success of the IC manufacturing industry. Accurate SEM-based imaging and measurement methods and models would allow the verification of conformance of the manufactured and designed IC structures on specified features.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Dimensionally Critical Nanomanufacturing

***Submitter*:** John Kramar

***Technological Innovation at Stake*:** Nanotechnology is predicted to have major positive impacts in a broad array of applications, including health care, homeland security, and communications. In order to turn this potential into a viable economic reality, the newly developed technologies must be grounded in accurate metrology to enable efficient process control and quality assurance. This is particularly true in dimensionally critical nanomanufacturing, where the performance of the product depends critically on the precise dimensions of specific features, and on the consistency of these dimensions throughout a manufactured product, or from device to device.

***Economic Significance of Innovation*:** Many reputable studies have predicted significant economic impacts for nanotechnology. For example, a recent National Science Foundation study projected a $1 trillion global market for nano products by 2015; private investment companies have offered similar estimates. This large economic potential is driven by the new properties and performance characteristics that occur at the nano level. The tools and devices segment is estimated to make up one third of the nano market, and within this sector, a large portion of products is expected to require highly precise dimensions.

***Technical Barrier to the Innovation*:** A key barrier to moving nanomanufacturing from the laboratory into the market place is the capability for well-understood, effective process control and product assurance.

***Stage of Innovation Where Barrier Appears*:** R&D (primary), Production (secondary)

***Measurement-Problem Part of Technical Barrier*:** In the nano regime, whereas many metrology forays have built up capability for addressing specific measurement needs, a truly versatile link to the SI unit of length is yet lacking. This versatility is critical for the flexibility to quickly address the quality-related metrology needs for yet-to-be-developed innovations and to shorten their time to market by enabling robust process controls.

***Potential Solutions to Measurement Problem*:** A flexible, multi-probe, long-range, three-dimensional, coordinate measuring machine with nanometer accuracy must be developed for realizing the unit of length in this domain. This capability will provide traceability for industry-developed factory-floor and quality control lab metrology instruments, via NIST- or industry-developed calibration artifacts.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Dimensional Metrology for Manufacturing Quality Control and Process Improvement

***Submitter*:** John Horst, Bill Rippey

***Technological Innovation at Stake*:** A standard data format for product design data, if developed, would tie feature data to the geometric dimensioning and tolerance data needed to manufacture products. Measurement system components from different vendors would then be able to exchange data effortlessly and without error. The inability to easily convey design tolerance information hinders the ability to build systems with advanced, automated capabilities.

***Economic Significance of Innovation*:** Currently, integration of components into systems is very costly and sometimes even impossible due to incompatibility of data inputs and outputs. The effort to translate formats, or to manually enter data into design and planning files expressed in proprietary formats, is costly, slow, and error prone. Exchange of data in a standard format will reduce the development and integration costs of multi-vendor components of metrology systems, achieve better inspection system capabilities, and enable better measurement results across corporate facilities.

***Technical Barrier to the Innovation*:** The effort to gain a consensus on a standard data format for product design data is hindered by the complexity of the data and the diversity of approaches to data flow. The barriers are typical standards challenges, requiring a public consensus effort to define a reference data flow architecture, to define the detailed information and its structure, and to specify an encoding format.

***Stage of Innovation Where Barrier Appears*:** End Use (primary), Production (secondary)

***Measurement-Problem Part of Technical Barrier*:** There is no comprehensive, cohesive definition of the data needed to support inspection planning, execution, and analysis. Parts of the data are defined in various standards or proprietary solutions that several vendors are developing at this time.

***Potential Solutions to Measurement Problem*:** To educate users and focus vendors, a first step would be to generate a modest scope, proof-of-concept demonstration of integration of computer-aided design (CAD), geometric dimensioning and tolerancing (GD&T) design/analysis, and inspection planning systems using a single data format. Stakeholders in production-oriented measurement systems need to develop a consensus standard that defines GD&T data assigned to product features in the product design phase. This information will serve as input to manufacturing production planning, inspection planning processes, and inspection results analysis.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Networking Sensor/RFID

***Submitter*:** Kang Lee

***Technological Innovation at Stake*:** Combining smart sensors and radio frequency identification (RFID) into wireless networks would yield innovative sensor systems ready for application in a variety of situations. Networking wireless sensors and RFID tags will help to create new business opportunities ranging from the consumer market (smart houses and appliances) to manufacturing processes (product improvement through better tracking and control) to the entire supply chain (asset tracking and management).

***Economic Significance of Innovation*:** The global sensor market is estimated to be $50.6 billion by 2008 from motor vehicle, process industries, machinery manufacturing and supplies, and office and building automation. The U.S. accounts for approximately 28% of this market. The size of the RFID industry is projected to be $5.8 billion by 2008. Sensors are playing a vital role in applications ranging from home and building automation to industrial automation to homeland security. Using wireless connectivity for sensor networks increases flexibility in deployment and reconfiguration, thus reducing the overall infrastructure cost. Combining RFID devices and smart sensors could expand the overall functionality and capability of the above applications.

***Technical Barrier to the Innovation*:** Wireless sensor and RFID tag technologies are being independently explored in industry, academia, and government. The notional idea of integrating the two technologies has just begun; however, some technical problems must be overcome before successful integration is achieved. The technical barriers include integrating and packaging the wireless sensors and RFID tags into single, small, low-cost devices for wireless networks, resolving security and privacy issues, and determining a means to verify the performance of the devices and networks.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The primary measurement problem inhibiting the introduction of these innovative sensor systems into the marketplace is verification of the performance of the combined wireless sensor/RFID devices, especially in a network configuration.

***Potential Solutions to Measurement Problem*:** Develop protocol testing, performance metrics, measurement techniques, evaluation methods, benchmarking techniques, and conformance testing. Achieve interoperability through standardization.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Precision Clock Synchronization

***Submitter*:** Kang Lee

***Technological Innovation at Stake*:** Precision-clock SYNchronization (PSYN) technology will be used for precision synchronization of process and control and for time-stamping of data in networked systems. PSYN will allow data time-stamping with unprecedented accuracy ranging from hundreds of picoseconds to sub-microseconds. Current technology and standards support target accuracy from sub-microseconds to tens of milliseconds.

***Economic Significance of Innovation*:** PSYN helps to attain more accurate timing to provide better products and services for customers and higher productivity through the increased accuracy of data delivery. With this accuracy increase of more than three orders of magnitude, PSYN will significantly improve the accuracy of data delivery and management, and thus enhance process improvements, which will result in cost reduction to industry. Presently submicrosecond timing is good enough for process equipment such as printing presses and wrappers. However, test and measurement instrument makers could make use of subnanosecond accuracy or better. Further, the telecommunication and home Ethernet communities would like to see hundred picosecond accuracy. The cost reduction is passed to the consumer. PSYN is expected to be used in test and measurement, telecommunications, utility and power, industrial automation and control and semiconductor process industries, and the military.

***Technical Barrier to the Innovation*:** The development of new types of devices employing PSYN technology for the market is being inhibited by incomplete understanding of the performance characteristics of both PSYN subsystems and their behavior when combined into networked systems. In particular, the absence of accurate calibration and characteristic measurements of subsystem devices and instruments utilized in networked systems using PSYN, security issues, and means of characterizing fault tolerance are holding back this innovation. Industry indicates that accurate measurement and calibration of subsystem devices to 250 picoseconds, traceable to national standards, are necessary to ensure confidence in the performance of the systems.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** There is an absence of trustworthy reference measurement methods for performance evaluation of the next generation of devices and instruments applicable for networked systems using PSYN.

***Potential Solutions to Measurement Problem*:** Develop protocol and performance testing and calibration methods for accurate measurement of devices and instruments used in PSYN systems. Achieving this will allow the development and commercial introduction of new classes of PSYN devices and instruments.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Safety Systems for Next Generation Robots

***Submitter*:** Nicholas G. Dagalakis

***Technological Innovation at Stake*:** The Next Generation Robot (NGR) is envisioned as a machine incorporating inherent safety design and benign operating features, which enable and promote lean manufacturing. The current state of robot technology has not changed significantly for the last ten years, and there are an increasing number of applications that could benefit from collaborative human-robot interaction.

***Economic Significance of Innovation*:** Current means of addressing the human-robot interaction safety problem involve restricting human access to significant portions of valuable manufacturing production floor space and investing significant resources in protective equipment. NGR, with built-in safety technology, is an enabling technology, which can affect the development of markets in those many classes of products requiring repeatable autonomous operation, handling of hazardous or heavy loads, etc. For example, this technology can reduce the cost of automobile manufacturing, microelectronic manufacturing, surgical operations, rehabilitation and elderly care, etc. There are at least 100,000 industrial robots in use in the U.S. and approximately 700,000 throughout the world. Approximately 10% of them are replaced annually. Their cost ranges from approximately $30K to $50K per unit. However, the cost of protective equipment is approaching the cost of the robotic units themselves. Overall, the current size of this market is approximately $4.2 to $7.0 B.

***Technical Barrier to the Innovation*:** A serious impediment of technological progress in this area is the potential for robots to cause serious injury when they come in close proximity to humans. Safety features must be built into the NGR and those features validated for effectiveness of protection.

***Stage of Innovation Where Barrier Appears*:** R&D (primary), Production (secondary)

***Measurement-Problem Part of Technical Barrier*:** Classification methods for the level of operating safety of a robot must to be established, as well as proof and certification methods that can be clearly communicated to regulators and users. The best safety equipment and standards will have no value if the regulators, managers and labor unions do not accept and promote them. Robot-human interface pain data need to be assessed as input to this classification scheme. There is also a need for sensors, controllers, or calibration tests that can prevent an unwanted robot arm motion and can measure the position and orientation of a 3D moving robot arm, even when it is obstructed from line of sight view in an industrial environment.

***Potential Solutions to Measurement Problem*:** Solutions could include computer simulations and tests with instrumented dummies, which can be used to validate safety claims and perhaps even rate robots according to their accident prevention capability. Collision detection devices designed to prevent collision with hardware should be redesigned to include human collision detection capability. The development of personal protective equipment that also alerts the robot controller of the identity, presence, location, status, training, and health condition of a human who has entered its restricted space is another potential part of the solution.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** Top Down Micro/Nano Manufacturing

***Submitter*:** Nicholas G. Dagalakis

***Technological Innovation at Stake*:** A central challenge of micro/nano manufacturing is the development of methods to build complex three-dimensional (3-D) micro/nano scale structures and devices using techniques that allow them to interface with the macro scale world (scale-up). Top down nano manufacturing refers to human-directed organization of nano scale components into structures, which must then interface with the macro scale world through some kind of scale-up interface. Top down manufacturing of these devices must be explored and standardized in order to allow for the economies of scale needed for successful production.

***Economic Significance of Innovation*:** This is an enabling technology, which can affect the development of markets in many new classes of products, which require accurate nano component 3-D position and orientation. For example this technology can accelerate the production of nano component, electronics, composite materials, sensors, fuel cells, etc. According to a Lux Research report, the nano technology products market could reach $2.6 trillion in approximately 10 years. Assuming this infrastructure gets put in place, an estimated 10 million manufacturing jobs worldwide – or about 11% of the total manufacturing jobs – may involve nano technology in that time frame. According to a SusChem report the nano technology machinery market is expected to grow by 30% per annum.

***Technical Barrier to the Innovation*:** Integration of micro and nano systems over multiple length scales ranging over orders of magnitudes is a challenge that must be met. Many factors make up this challenge, including: raw material supply and product transport, precise and inexpensive arrays of fast parallel 3-D human directed manufacturing cells, massive parallel controls, sensors, fast imaging, scale-up interfaces. Manipulation, placement, actuation, and packaging of nano devices such as nano tubes, nano particles, or single molecules is a largely unexplored area.

***Stage of Innovation Where Barrier Appears*:** R&D (primary), Production (secondary)

***Measurement-Problem Part of Technical Barrier*:** Fast and precise positioning and manipulation require accurate mathematical models, force, position and velocity sensing. Due to design required fabrication process variations, it is necessary to know mechanical properties of materials and the shapes of surfaces and features in hard to reach places, at different locations and orientations of a die. Since contact of fast moving objects might be necessary, it will be required to know the tribological, static friction, and wear properties of the materials involved.

***Potential Solutions to Measurement Problem*:** Develop micro/nano sensors that can be embedded into fast moving devices. Develop compact models using controlled physical signals as input and material mechanical properties of dies at different positions and orientations as output. Identify nondestructive measurement methods for the shape of surfaces and buried structures.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Manufacturing Simulation Validation

***Submitter*:** Charles McLean

***Technological Innovation at Stake*:** If available, validated manufacturing simulation could play a large role ensuring the feasibility of new manufacturing capabilities and their performance. Manufacturing industry and researchers have predicted many diverse products based upon nano/meso/micro, robotic, semiconductor, composite material, fuel cell, and pharmaceutical technologies. These products will require the development and construction of new manufacturing plants, production lines, and process equipment. The manufacturing systems for these new products will undoubtedly be very costly. If these new manufacturing capabilities are not implemented in a cost-effective and efficient manner, invested resources will be wasted, and the growth of these technologies will be slowed. Validated manufacturing simulations can increase the likelihood of successful implementation of these manufacturing capabilities.

***Economic Significance of Innovation*:** As an example, an Intel semiconductor fabrication plant cost between $2.5 B and $3 B in 2003. A similar plant is expected to cost $6 B in 2007. If new manufacturing capabilities such as these cannot be operational and profitable in a brief time, U.S. investment in the new technology will undoubtedly dry up. Technically correct, that is, validated, simulations, could become a key U.S. a competitive advantage in minimizing waste and maximizing efficiency in bringing new manufacturing capabilities on line in new technology areas. The U.S. is a leader in simulation, but other regions of the world are gaining fast both through corporate acquisitions and new technology development.

***Technical Barrier to the Innovation*:** A reliable validation process, established on sound scientific principles, is needed to help ensure the correctness of manufacturing simulation models. General-purpose manufacturing simulators and simulation support tools have been available for some time. However, considerable development effort and technical modeling expertise are necessary to create the models representing the specific design and engineering problems associated with a manufacturing system. Unfortunately, the application of simulation technology has been more of an art than a science. There is currently no way to be sure that a simulation will correctly predict the behavior (overall functionality, quality, cost, and timing performance issues) of the modeled manufacturing system.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** There are no standard procedures available to validate manufacturing simulation models in the new technology innovation areas. Furthermore, there are no standard test-data sets available to ensure that simulation software is capable of producing the correct outputs given a properly validated model.

***Potential Solutions to Measurement Problem*:** Establish a technical foundation for standard manufacturing simulation validation procedures. Develop test data sets representative of major U.S. manufacturing sectors.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Carbon Nanotube Materials

***Submitter*:** Kalman Migler

***Technological Innovation at Stake*:** Nanotube materials possess an extraordinary combination of materials properties: strength, thermal conductivity and electronic properties. Successful incorporation of nanotube materials into a broad-range of critical technologies including fuel cells, semi-conductors, sensors, fibers, displays, and composite materials will yield revolutionary advances in product performance. As one example, in fuel cell applications, the nanometer scale and novel chemical characteristics of Single Wall Nanotubes (SWNTs) give them profound advantages as electro-catalyst supports and enable the fabrication of "free standing" fuel cell electrodes considerably more powerful than those currently in use.

***Economic Significance of Innovation*:** In the automotive arena alone, the DOC Office of Technology Policy (OTP) projects a $70 billion market at stake for vehicles powered by fuel cells. FreedomCAR describes the necessary performance/cost requirements of the fuel cells that include 60% efficiency at a price of $30/kW. Nanotube based fuel-cells are leading contenders to meet these requirements

***Technical Barrier to the Innovation*:** The quality (e.g. length, diameter, distribution…) and purity (e.g. levels of carbonaceous impurities and residual catalyst) of nanotubes is preventing high-tech applications because they require reliable and consistent materials of a given sub-type. All nanotube materials are comprised of dozens of subtypes of nanotubes that differ in length, diameter and electronic properties. There are no accepted methods of characterizing nanotube samples for these parameters, hindering trade and, there is no technique that allows a manufacturer to isolate and identify the appropriate type of nanotube needed for a given product.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** In order to for a manufacturer to provide nanotube materials of specified length, diameter and chirality, they need quantitative measurement techniques to characterize their samples, so that techniques to sort them by these characteristics can be developed.

***Potential Solutions to Measurement Problem*:** Development of solution based chromatography to sort the nanotubes, coupled with quantitative spectroscopic methodology to efficiently determine the nanotube type. Development of precision control of growth of nanotubes.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue**:** High Magnetic Field Technology

Submitter**:** Peter Gehring

Technological Innovation at Stake**:** Advances in MRI and NMR technology depend on new materials for superconducting (SC) magnets. High magnetic field environments have many applications. Functional magnetic resonance imaging (fMRI), a diagnostic tool to image organs, is revolutionizing neuroscience; optically pumped magnetic resonance techniques allow visualization of new quantum phenomena in semi-conductors; ion cyclotron resonance mass spectroscopy is an important tool with which to determine the chemical composition of complex systems.[1] High-resolution NMR techniques are essential to drug discovery and development.

Economic Significance of Innovation**:** Demand for stronger magnets is growing and stems from resulting improvements to MRI S/N ratio and resolution, complex molecular structure determination by NMR, and the ability to study smaller samples. Commercial MRI systems make up the largest share of the SC magnet market. Worldwide MRI sales are forecast to rise from $2.4B in 2000 to $3.5B in 2010.[2] The fast increasing roles played by MRI and NMR in the healthcare industry imply a significant opportunity cost if present magnet technology remains flat. In addition, the worldwide market for electric motors rated above 1000 HP is $1.3B per year. Such motors use 30% of all electricity generated in the US. Conversion to high T_c SC ceramics would reduce size and losses by 50%, improve stability, and would be a major benefit for applications such as ship propulsion.[3]

Technical Barrier to the Innovation**:** Magnet performance is limited by materials current density and strain tolerance. No superconductor can provide 100 Amperes/mm^2 at 1 GHz (23.1 Tesla). SC alloys of niobium and aluminum may prove useful; the 90 K ceramic high-temperature superconductors are brittle and difficult to form into solenoid coils.

Stage of Innovation Where Barrier Appears**:** R&D

Measurement-Problem Part of Technical Barrier**:** Materials chemical and magnetic structure, and spin and lattice dynamics, are difficult to measure under high magnetic field conditions because small magnet bores severely limit sample size and access.

Potential Solutions to Measurement Problem**:** Development of supporting instrumentation at the National High Magnetic Field Lab, including design and construction of low and high temperature capable NMR probes; and advances in pulse sequence methodology. New instruments for neutron and x-ray scattering studies of materials under high-field environments should be developed. Establish a consortium to foster development of magnet technology.[1]

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Sub-Surface, In-plane Structure Characterization for Magnetic Data Storage

***Submitter*:** Julie Borchers

***Technological Innovation at Stake*:** To meet projected roadmap areal storage density growth (1 Tbit/in^2 in products by 2014) for hard disk drives (HDD), magnetic storage firms will create bit-patterned media, track-patterned media and self organized magnetic arrays (SOMA) with confined lateral dimensions to reduce bit sizes. Advances have led to disk prototypes with nanoscale-featured patterned films and SOMA. The aim is a noncorrosive, durable coating uniform over 0.5” – 3” diameter disks with individual 5 – 10 nm particles or pillars, each corresponding to a single bit and comprising a single ferromagnetic domain at room temperature.

***Economic Significance of Innovation*:** The push for large HDD storage capabilities on desktop computers and small portable products, such as, cell phones, PDAs, digital still cameras, and digital video cameras, could increase the hard HDD market from 372.2 million units in 2005 to 408.3 million units in 2006, according to a recent report of The Information Network (TIN). The HDD market is expected to grow from $3.3 billion in 2005 to $4.5 billion US in 2009 according to Gartner Dataquest. By meeting the roadmap, HDD’s will satisfy anticipated multimedia library storage demands in micro and mobile devices.

***Technical Barrier to the Innovation*:** Manufacturing will require nanoscale features (e.g. thickness, width, roughness, magnetization) to be uniform over the entire surface of each disk and reproducible from disk to disk. Current prototypes do not have the uniformity needed for long-term stability.

***Stage of Innovation Where Barrier Appears*:** Research and Development; Production

***Measurement-Problem Part of Technical Barrier*:** During development, it is difficult to characterize underlying magnetic layers used to stabilize the pillars and the matrix used as a template for SOMA. Existing measurement tools (i.e., mostly microscopy) are not capable of precisely determining the thickness, composition, interface roughness and magnetization of nanometer-scale features. These techniques sample small areas which are assumed to be representative of the entire disk. The absolute magnetic moment of the disk features must be measured and calibrated relative to a traceable, stable thin film standard for magnetic moment in the range of 10^{-7} Am^2 (10^{-4} emu). Currently, the smallest traceable standards are specified for moments of order 10^{-4} Am^2 (0.1 emu), and they do not have thin film shape.

***Potential Solutions to Measurement Problem*:** Development of neutron diffraction techniques, such as SERGIS (spin-echo resolved grazing-incidence scattering) that provide a 2-D map of the depth-dependent structure (i.e., chemical and magnetic) in film devices with nanoscale resolution. Refine existing polarized neutron reflectivity techniques to measure absolute moments in thin films. Development of synchrotron-based x-ray techniques, such as x-ray spectro-holography, that provide a real-space image of magnetic nanostructures with nanoscale resolution; R&D to push the resolution limits of AFM’s, MFM’s and other microscopy techniques; Thin film magnetization standards for calibration and/or gauging of production line magnetometers. Moments should correspond to Ni films in a range from 3 nm to 1 micron.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Ambient Temperature Stabilization of Biomacromolecules

***Submitter*:** Marcus Cicerone

***Technological Innovation at Stake*:** DNA and proteins serve as the basis for cytokines in tissue engineering, and for vaccines and bio-defense agents. Further, they offer the promise of a wide variety of unique treatments for human diseases. However, to be economically viable, the therapeutic macromolecules must be stabilized against chemical and physical degradation in the interval between manufacture and use. Broad availability necessitates that the stabilized protein be insensitive to temperature swings; the most effective means currently available for doing this is to store them in a dried, glassy solid.

***Economic Significance of Innovation*:** More than 75 protein-based medicines have received FDA approval (for specific limited shelf lives). These had sales of nearly $33 billion in 2002, showing the highest rate of sales growth of any drug class in the last decade, and address a variety of conditions, including cancer, arthritis, asthma, and multiple sclerosis. The Pharmaceutical Manufacturers Association reports that over 360 new such medicines are in the pipeline, or about a third of all new drugs under development (PhRMA Industry profile 2002). Instability of a protein formulation may result in a loss of potency, unintended immune response, anaphylactic shock, and death.

***Technical Barrier to the Innovation*:** Inherently marginal stability of proteins poses a great challenge in bringing any protein-based product to market, where a shelf life of 18-24 months is typically required for economic viability. Formulation of stabilizing glasses is a major technical barrier. At present, there is no reliable set of parameters for rapidly evaluating candidate formulations.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** It is not presently possible to determine precisely which glassy formulations will stabilize proteins well and which will not. As a consequence, formulations are designed empirically, and many poorly optimized formulations are tested over the full shelf life span, significantly driving up costs of bringing these drugs to market; formulation costs can even exceed discovery costs.

***Potential Solutions to Measurement Problem*:** Several materials parameters have been identified thus far as being important indicators of stabilizing ability of a glassy formulation. Routine and precise measurement techniques must be developed to measure such parameters as protein / glass interaction enthalpy, picosecond-nanosecond (ps-ns) materials dynamics, and others that turn out to be important to this problem.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Electronic Packaging

***Submitter*:** William J. Boettinger

***Technological Innovation at Stake*:** Conversion to lead (Pb) free solder finish on electronic components is hindered by the emergence of short circuits due to the growth of tin (Sn) whiskers in Pb-free, Sn-based alloys. The whiskers are a reliability risk for any application of electronic assemblies using tin plated components (see NRC Information Notice #2005-25), particularly if the system is expected to operate for more than five years.

***Economic Significance of Innovation*:** Japan and Europe are legally bound to Pb-free technology starting in 2006. US industry must follow suit to maintain green image, to make international sales and maintain interchangeability of design. Ron Gedney,of iNEMI says,"Using my IBM experience, a field failure from tin whiskers would cost many millions of dollars to fix and repair, and, more importantly, result in lost customers."

***Technical Barrier to the Innovation*:** Industry continues to study whisker formation without assessing the compressive stress driving the phenomenon. X-ray diffraction (XRD) measurements of stress provide a rapid, nondestructive test method. Such measurements will serve as a research tool and quality method to identify which manufacturing methods, (plating, reflow, annealing, etc.) lead to benign tensile stress. Such measurements require high precision to measure whisker growth stresses ≈ 10 MPa. According to a request sent to NIST by an industry working group sponsored by iNEMI, "there are few laboratories that can make the measurements and there are no proper standards against which to assess the resulting data." Commercially available standards for stresses ≈ 1000 MPa, while good for the general calibration of XRD methods are insufficient for this problem.

***Stage of Innovation Where Barrier Appears*:** R& D; Production (quality control)

***Measurement-Problem Part of Technical Barrier*:** Low compressive stresses affecting whisker formation necessitate highly accurate film stress measurement. Although XRD is a well-established technique for stress measurement and there are generic guides on stress measurement good practice available in the public domain, a specific guide for both stress measurement and critical review of experimental results for Sn would be beneficial to the tin plating community.

***Potential Solutions to Measurement Problem*:** At least five problems need to be addressed: (i) in-situ calibration of the diffractometer during stress measurement using conventional $\sin^2\psi$ method, (ii) conversion of strain measurements to stress using proper anisotropic elasticity theory, (iii) proper consideration of preferred orientations in the tin electrodeposits, (iv) proper consideration of residual stress gradients that can exist through the thickness of the electrodeposit. (v) independent confirmation of x-ray results . X-ray results can be complicated by large grain size, the noncubic nature of Sn and the crystallographic texture of the samples.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Multilayer film structures for electronics and optics industries

***Submitter*:** Donald Windover

***Technological Innovation at Stake*:** Multilayer, nanoscale, novel material, thin films with enhanced uniformity and reproducibility are key to achieving higher component densities, faster operating times, and more efficient energy usage in microelectronic devices. Some examples include high-k and low-k replacement of SiO^2 in both gate and interconnect applications and new "strain-enhanced" device substrates for the CMOS process.

***Economic Significance of Innovation*:** All advanced nano-devices and microelectronics structures, such as CMOS gate and interconnect applications, bio-chemical sensors, and flat-panel displays, use multilayer, nanoscale thin film structures in processing. Improvements in layer deposition control, therefore, could simultaneously impact multiple electronics industries. As an example, improved "in-process" monitoring of thin film deposition enhances device-manufacturing-yield increasing profits for the semiconductor industry (39 billion dollar US market / 166 billion dollar worldwide in 2004 according to SIA - http://www.sia-online.org).

***Technical Barrier to the Innovation*:** Repeatable deposition parameters for ultra-thin films (i.e., uniformity, thickness, surface roughness, and composition) are essential for reliable production and operation of semiconductors and electronics.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Precision and repeatability in determination of film properties, calculation of correlations, and estimation of model and instrument error bounds all present current technical barriers requiring fundamental modeling of method and instrumentation, and calibration artifacts currently unavailable to industry.

***Potential Solutions to Measurement Problem*:** X-Ray Reflectometry (XRR) provides the required determination of thickness, density, and roughness with high precision via model refinements of the structural parameters for certain material systems.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Active Implantable Medical Devices (AIMDs)

***Submitter*:** Elizabeth Drexler

***Technological Innovation at Stake*:** Highly reliable AIMDs, defined as having <0.1% failure rate due to materials, design, manufacturing, or handling.

***Economic Significance of Innovation*:** AIMDs are projected to be a $10B/year industry by 2007, and range from implanted hearing assist devices to deep-brain neurostimulators. The economic significance of this industry can be measured in dollars, productivity, quality of life, and life itself. Depending on the clinic, 1–8.3% of cochlear implantations end in hard failures (design errors and head traumas). Replacement of the device costs approximately $30K for the surgery with a 3-day recovery time. The cost of device failure can be even higher, as is the case with Guidant's implantable cardioverter-defibrillator (ICD) that was recalled in 2005 due to a design flaw that allowed body fluid to penetrate the canister resulting in short circuits. 109,000 units were recalled, and recently a 7^{th} death was attributed to the defect. The economic significance is measured in surgical costs for retrieving and reimplanting the ICDs, the cost of recovery time and lost productivity, loss of sales due to loss of consumer confidence, litigation costs, and the loss of life.

***Technical Barrier to the Innovation*:** Some unknown, but significant portion of the hard failures in AIMDs are due to body fluids infiltrating the canister containing the battery and the electrical circuits, which can cause corrosion and short circuiting. Failures occur despite the device complying with existing standards. Existing leak-rate tests and standards were designed for space applications, not medical applications where the device is implanted long-term in a bioactive environment with 100% humidity.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** AIMDs cannot be properly assessed, nor held to higher reliability standards with the present technology. There are no test techniques that will quantitatively measure leak rates of less than 10^{-9} cm^3/s, so standards cannot be written or required. The high failure rate also is evidence of the need for suitable accelerated reliability tests for lifetime predictions.

***Potential Solutions to Measurement Problem*:** New leak rate tests need to be developed that are at least 3 to 4 orders of magnitude more sensitive, as well as being reproducible, traceable, and affordable or accessible. Once a standard test technique and methodology have been established, new test standards must be written through an established standards organization, so that the Food and Drug Administration (FDA) can require compliance for every new device design.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Novel Materials for Nanoscale Diffusion Barriers in Microelectronics**.**

Submitter: Daniel Josell

Technological Innovation at Stake: To successfully achieve future generation devices, the microelectronics industry is examining a large number of nontraditional materials for applications at both the semiconductor device and the interconnect levels. These include new materials for gate-stack structures and wettable diffusion barriers for interconnect levels. Novel materials combinations for other nanoscale applications are also being developed. Successful implementation of new materials in nanoscale structures requires barrier layers to separate incompatible materials, e.g., inhibiting copper diffusion from interconnect levels to the wafer surface where the presence of copper destroys transistor operation. Efficiently evaluating the efficacy of these diffusion barriers is complicated by the number of potential materials systems and the low throughput and high cost of techniques presently used to quantify mass transport through diffusion barriers.

***Economic Significance of Innovation*:** Semiconductors, itself a large industrial sector ($213B worldwide market), is also an enabling technology that creates value and benefits for numerous other applications including military electronics, computing, industrial automation, telecommunications, and consumer electronics. Although this industry is faced with many technological issues, successful identification and development of new barrier materials is critical if the industry is to achieve devices manufacturing at the 35 nanometer level and below. Innovative materials can contribute to the advances needed in the semiconductor industry and the aforementioned industries that it directly impacts.

***Technical Barrier to the Innovation*:** There are a large number of potential materials systems that require investigation. While the electronics industry utilizes capacitor leakage structures for assessing barrier layer efficacy both rapid and inexpensive, cannot quantify mass transport and is useful for only a limited range of materials. For more general materials systems, the severity of some requirements, coupled with the length scales of interest, limit study to time-consuming, cost- and equipment-intensive approaches that impede examination of new materials.

Stage of Innovation Where Barrier Appears: Production

***Measurement-Problem Part of Technical Barrier*:** Absence of rapid and accurate approaches suitable for assessing mass transport through all classes of materials limits data available for predicting the long-term stability of nanostructures. Measurements of mass transport at the nanoscale utilizing standard x-ray diffraction equipment and multilayer specimen geometries coupled with thermodynamic and scattering analyses could substantially accelerate materials evaluation. Such an approach, while capitalizing on readily available instrumentation, would still require development of experimental methodologies and models for data interpretation. Combinatorial or high-throughput techniques would also needed for assessing diffusion through barrier materials in nano-structured devices to address the broad range of technologically relevant materials systems.

Potential Solutions to Measurement Problem: X-ray diffraction is ideally suited for rapid and accurate examination of nanostructure evolution. Development of thermodynamic and x-ray scattering models to interpret diffraction results from multilayered structures would permit universal, rapid evaluation of mass transport at nanometer length scales.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Spectroscopic Data Analysis in the Criminal Justice System

***Submitter*:** William E. Wallace and Anthony J. Kearsley

***Technological Innovation at Stake*:** Forensic analysts fight crime and international terror by linking perpetrators with crime scenes through the use of chemical analysis derived from state-of-the-art chemical spectrometers. Spectral interpretation is a critical component of this complex activity that utilizes a variety of analytical protocols and methods that currently rely to some degree on the judgment the forensic analyst. Differences in spectral interpretation result in confusion both in trial settings and in case development by law enforcement authorities. Improved analysis methods that reduce or eliminate the need for judgment on the part of the forensic analyst has the potential to significantly improve the validity of chemical analysis used for forensic purposes, thereby improving the effectiveness of the U.S. judicial system and the ability of the U.S. to combat terrorism.

***Economic Significance of Innovation*:** Better use of chemical spectroscopy by forensic scientists would lead to a greater conviction rate and the subsequent removal of criminals and terrorists from the streets. The expertise and intuition of the analyst that plays a pivotal role in data interpretation often leads to significant weakness in the legal case against criminals and terrorists. Defense attorneys have little difficulty impugning the credibility of the prosecution chemist especially when no firm theoretical basis for data analysis has been established.

***Technical Barrier to the Innovation*:** Many methods used in spectral analysis are typically ad hoc and poorly understood. Standardization of mathematical methods is needed that gives objective and accurate spectral data. Additionally, new chemical analysis methods, testing protocols, case studies, physical and procedural standards) are needed by the forensics community.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Every spectrum obtained from a sample contains some degree of error caused by sampling procedures, spectroscopic instrument characteristics, and varying levels of contamination and result in spectral artifacts. These artifacts need to be understood and explained in detail by the chemical spectroscopist/forensic analyst, who is required to use their judgment in dealing with the noise characteristics of particular analysis tools. Development of spectral analysis methods based on rigorous mathematical approaches coupled with broad agreement as to their utilization in interpreting chemical spectra can significantly reduce confusion.

***Potential Solutions to Measurement Problem*:** Develop and introduce more-robust numerical methods for data analysis. Produce standards that aid the forensic analyst to determine the uncertainties for their specific measurement.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Nanomanufacturing

***Submitter*:** J. Cline

***Technological Innovation at Stake*:** Nano-materials hold forth the promise of unprecedented potential to design devices with unique properties and capabilities. Requisite to realization of these devices, however, is the ability to quantitatively measure nanoscale features of these structures. These measurement data will permit the understanding of origin of the properties these devices exhibit, and, therefore, their optimization.

***Economic Significance of Innovation*:** Nanomaterials are being pursued as the basis for next-generation developments in a wide range of applications, including high-density electronics, sensors for biochemical applications, actuators in nanomechanical devices, and biomedical diagnostic and delivery mechanisms. The Nanotech Report (2003) projects a $1 trillion nanotechnology industry by 2015.

***Technical Barrier to the Innovation*:** Nanomanufacturing requires an understanding and control of the adhesion and bonding of the surfaces, particles, and nanoelements comprising a nanodevice. Interactions at the nanoscale, however, are highly dependent on the composition of the surface layers, size, and composition of the nanoparticles. Traditional analysis methods and assumptions, such as those based on bulk crystalline structures, are known to be inaccurate and the cause of erroneous models.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** A primary challenge is to achieve a reliable, quantitative measure of the nano-particle surface layer thickness, size, crystalline perfection and interatomic spacing.

***Potential Solutions to Measurement Problem*:** Diffraction methods are predicated on the presence of crystalline structures and are well suited to measurement of features of nanomaterials that are inaccesable by alternative methods. The combination of high resolution x-ray diffraction metrology and standard reference materials certified for crystallite size, amorphous content, and lattice parameter are key to an industry accessible measurement procedure for assessing quantitatively character of nanomaterials.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** High Speed Magnetic Domain Observation for High Efficiency Electrical Transformers

Submitter: Robert Shull

Technological Innovation at Stake: Devices that generate electricity, consume it to perform mechanical work in electric motors, actuate mechanical motion in myriad applications, and transform it to various voltage levels are ubiquitous in an industrial society. All use the magnetic properties of materials to achieve this transformation, are most often called transformers, and range in size from those found in many electronic devices to those critical to effective electric power distribution. Higher efficiency transformers will result from improvement of magnetic material switching behavior, which is dependent upon a material's ability to reverse the magnetic field direction, the so-called coercivity. Low coercivities result in minimizing the amount of energy lost in magnetic field reversal manifested in a transformer as its rise in temperature due to loss of electrical energy in the form of heat.

***Economic Significance of Innovation*:** Improvements in magnetic material coercivity will result in significant economic benefit through reduced energy usage throughout the U.S. economy. Annual electricity consumption of the U.S. was 3,656 billion kilowatt hours, or $271B at $0.0742/kwh, in 2003. Because almost all transformation of electrical power from one voltage level to another utilizes magnetic materials, any incremental improvement in their coercivity will translate directly to reduced thermal loss.

***Technical Barrier to the Innovation*:** The coercivity and the speed at which switching occurs depends intimately on the magnetic switching mechanism. The least energy consuming switching mechanism occurs through nucleation and growth of local domains with reversed magnetization. Visualization of the nucleation and growth behavior of magnetic domains at high speeds provides a means to observe magnetic domain formation and movement. Such capabilities are not currently available and have excellent potential to provide new insights into the mechanisms that control magnetic domain reversal.

Stage of Innovation Where Barrier Appears: R&D

***Measurement-Problem Part of Technical Barrier*:** There are only a few methods for visualizing magnetic domains and these do not have sufficient time resolution to provide images at speeds significantly in excess of commonly used power distribution frequencies, i.e., 50 and 60 Hz. Successful investigation of magnetic domain switching mechanisms can be significantly improved by the capability to visualize and observe switching with faster time sampling. Magneto-optical methods offer promising capabilities and have been developed with relatively slow temporal resolution, but suffer from low intensity light emission. New approaches such as magneto-optic indicator film (MOIF) methods are needed to support measurement at high speeds.

Potential Solutions to Measurement Problem: Use of femtosecond (10^{-12} s) laser illumination techniques has good potential as a tool for investigation of the nucleation and growth of domains during magnetization switching. Results of such investigation can lead to improved models of the mechanisms controlling magnetic domain switching, better models of this behavior will result in improvements to transformer materials.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Higher Efficiency Refrigeration Based Upon Room Temperature Magnetics

Submitter: Robert Shull

Technological Innovation at Stake: Magnetic refrigeration has the potential to provide an alternative cooling technology to traditional refrigeration with better Carnot efficiency, fewer moving parts, no vibrating compressor, and no chlorofluorocarbons. Development of a practical, room temperature, magnetic refrigeration process could result in significant reductions in oil consumption, eliminate the background noise of home refrigerators, and largely eliminate the need for a class of greenhouse gases.

***Economic Significance of Innovation*:** Yearly, households in the U.S. use approximately 0.4 Quads of electrical power for refrigeration. Efficiency increases due to improved refrigeration cycles have potential for significant cost savings, if costs of replacement technologies are similar to those of current, less efficient, mechanical refrigeration methods. An additional societal benefit is reduction in the proliferation of CFCs to the atmosphere, thereby contributing to an improvement of the health and well-being of the general population.

***Technical Barrier to the Innovation*:** Presently, magnetic refrigeration is a good low temperature and high magnetic field technology. To make it useful at room temperatures and at magnetic field levels found in permanent magnets, new refrigerant materials need to be developed. The methodology for efficient measurement and comparison of magnetic properties of materials are needed. In addition, new paradigms for developing improved refrigerants need to be designed since the present methodologies, despite being partially successful, are scientifically not correct, and much more improvement in magnetic refrigerants is required before they can be shown to be economically competitive with current technology and, and therefore, reach the marketplace.

Stage of Innovation Where Barrier Appears: R&D

***Measurement-Problem Part of Technical Barrier*:** Measurement of magnetocaloric effects is most easily realized by using magnetization measurements. However, the attractive materials for magnetic refrigerants are ferromagnets that exhibit large hysteresis losses and consequently their magnetization is not independent of the applied field. This is because in the presence of large hysteresis the magnetization is not a single valued function of the field but dependent on magnetic history. Current methods for calculating magnetocaloric effects from the magnetization data through the use of the Maxwell relation are therefore not appropriate. In fact, the Maxwell relation, derived from equilibrium thermodynamics, can only be correctly applied when the magnetization is nearly a single valued function of the magnetic field. Although more scientifically robust methods exist, this simpler approach is sometimes used. In addition, methods for accounting for hysteresis losses in calculating magnetic refrigerant properties must be developed. Lastly, a methodology for efficiently surveying the performance of prospective magnetic materials through direct thermal measurements is needed. Further development of improved refrigerants is partially limited by the lack of these methodologies. Significant efforts are now underway that use incorrect approaches to determine magnetic characteristics. These approaches can mislead by identifying inappropriate materials as having desirable magnetic properties. To address this issue, experts in magnetism and magnetic materials need to focus on the problem of calculating entropy appropriately, in systems with pronounced hysteretic behavior where there is no reversibility of magnetization.

Potential Solutions to Measurement Problem: New models are needed, as well as R&D for support and validation.. Measurements are also needed of thermal effects in different systems using these new models.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** Magnetic Sensors

***Submitter*:** W. F. Egelhoff, Jr

***Technological Innovation at Stake*:** Measurement and mapping of ultra-low magnetic fields (on the order of 1 pT) using inexpensive, solid state, room-temperature sensors could revolutionize many technologies by providing data not currently available in the fields of nondestructive failure analysis for microelectronics, battlefield/unattended ground sensors, toxin detection for homeland security, and biomedical research such as magnetic bead tracking and magnetic imaging of neural activity . (e.g., routine high-resolution imaging of the beating heart in real-time would revolutionize cardiology)

***Economic Significance of Innovation*:** The diversity of potential applications is so great, and it is so difficult to predict which ones will be successful, that one can only say that products with billion-dollar markets are likely. For example, magnetocardiograph instruments for imaging the beating heart are presently only used as research tools. If the cost could be reduced to about $1M, they would be affordable for all of the nation's 6000 hospitals for rapid routine diagnostics of patients with heart problems.

***Technical Barrier to the Innovation*:** – In these devices, magnetic noise is the critical issue. There are two basic types of magnetic noise: intrinsic, due to thermal fluctuations of the fundamental modes of the system, and extrinsic, due to thermal fluctuations of defects. Significant research findings in this field could lead to the advanced capabilities envisioned.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The key to success will be improving the state of the art in measurements of both intrinsic and extrinsic magnetic noise by a factor of about 1000. That improvement will permit the measurements and analyses required to develop ultra-low field magnetic sensors.

***Potential Solutions to Measurement Problem*:** A concerted program is needed for making new magnetic noise measurements, for theoretical modeling to understand the nano-structural origins of the magnetic noise, for fabrication of novel magnetic materials that will be nano-engineered to have ultra-low magnetic noise, and for designing and evaluating prototype sensors that integrate all aspects of the optimized properties. All of this will go towards the optimization of the reduction of magnetic noise.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Structural Safety Assessment

***Submitter*:** Tom Siewert and David McColskey

***Technological Innovation at Stake*:** In response to a heightened interest in safety and security, owners of existing and planned structures desire a more accurate assessment of the expected response of their structures to extreme events such as fires, seismic events, hurricanes, and explosions from sources such as gas leaks or terrorist attacks. These structures include buildings, bridges, offshore structures and pipelines.. The understanding of material behavior under extreme conditions, that does not exist today, would enable the creation of these more robust safety assessment procedures, mainly in the design and construction of new structures.

***Economic Significance of Innovation*:** The US Government (alone) spends $50 billion dollars per year on new structural buildings, and its current investment is in the trillions of dollars. The total US investment in building structures is several times larger. Similar to the retrofits to building connections after the Northridge earthquakes, building owners are considering various expensive safety retrofits to improve safety for building occupants and first responders. Wrong choices could waste billions of dollars, cost lives, and not really improve safety. Similarly, the repair and replacement of offshore structures and pipelines in the Gulf of Mexico, due to Hurricane Katrina alone, is estimated to cost in the billions of dollars. Earthquakes are California's costliest disasters. They have produced over $60 billion in losses since 1971 to buildings and bridges. Damage to bridges in the greater Los Angeles area due to the Northridge earthquake was estimated at $150 million. Over $2 billion was spent to repair and retrofit bridges in the San Francisco Bay area following the Loma Prieta earthquake.

***Technical Barrier to the Innovation*:** Evaluations of structures (buildings, bridges, offshore structures and pipelines) requires data for extreme conditions (i.e. high temperatures for fires and high strain rates for high-speed impact or explosions) and complex models. Structural databases today tend to be based on static materials properties developed at room temperature (the expected condition). High temperatures decrease the yield strength and modulus of steels and high strain rates typically increase the yield strength of steels. The relationship is often non-linear, therefore being extremely difficult and expensive to derive.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The lack of high strain rate and high temperature data on structural materials inhibits the modeling for the safety assessment of structures. For example, the accurate modeling of the World Trade Center required 2 years of mechanical testing on unique and common structural steel alloys so that the requisite data could be obtained and the structures properly modeled.

***Potential Solutions to Measurement Problem*:** Research to develop an extreme event (high temperature and high strain rate) database for structural steels, and the development of structural finite element models that can be used by the appropriate authorities and agencies for safety the assessment of structures. Existing models tend to evaluate a structure's response to a static load at a fixed temperature (usually ambient). The advanced models would handle the varying response as the loading rate and/or temperature changes for various possible scenarios.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Hydrogen-Storage and Fuel-Cell Materials and Devices

***Submitter*:** Terrence J. Udovic

***Technological Innovation at Stake*:** Energy systems of the near future will have to be cleaner and much more efficient, flexible, and reliable than they are today in order to ensure America's energy security and environmental viability.

***Economic Significance of Innovation*:** Hydrogen-powered fuel cells are being promoted by our government and embraced by industry as a solution to our dependence on petroleum imports, poor air quality, and greenhouse gas emissions. Making this "hydrogen economy" a reality is a major goal of the President and of the 2007 budget..The economic impact accompanying the transformation from energy systems based on fossil-fuel combustion to those based on hydrogen-powered fuel cells is staggering. According to the Energy Information Administration, in 2004, total U.S. energy expenditures were $871 billion, and the U.S. consumed 100 quadrillion Btu's of energy, ~28% by the transportation sector. The U.S. alone used about 21 million barrels of oil per day (~$6.5 billion/week assuming $45/barrel). Replacing even half of these barrels cuts our dependence on oil by ~$250 billion/year in today's dollars.

***Technical Barrier to the Innovation*:** The performance of hydrogen-powered fuel cells, particularly in vehicles, is critically compromised by (1) low hydrogen-storage capacity and poor cycling characteristics of current solid-state hydrogen-storage media, and (2) below-par fuel-cell devices due to property deficiencies in current device materials and debilitating, poorly-understood, water-management problems during operation. Industries such as GM recognize that these problems ultimately lead to poor performance and reliability. .

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The timely and successful transition to a hydrogen economy requires in-situ, unique, hydrogen-sensitive probes with advanced capabilities to assist in (1) the fundamental, atomic-scale to nanoscale characterization of newly discovered hydrogen-storage and fuel-cell materials with potentially improved properties, and (2) the nanoscale to microscale real-time imaging of both hydrogen-storage tanks during cycling and fuel-cell devices during operation. This will help assure needed performance in automotive and other applications. .

***Potential Solutions to Measurement Problem*:** Powerful, non-destructive neutron-based probes should be developed and refined together with customized sample geometries tailored to address the demanding requirements of measuring (1) highly neutron-absorbing and/or increasingly complex hydrogen-storage and fuel-cell materials, and (2) real-time tomographic images of next-generation hydrogen-storage tanks and fuel-cell devices.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Nanomanufactured Components in Complex Fluids

***Submitter*:** Kathryn L. Beers

***Technological Innovation at Stake*:** Industry is particularly eager to incorporate nanostructured components (e.g. nanoparticle and block copolymer assemblies, protein and peptide complexes, functional dendrimers and other engineered macromolecules) into their formulations because these additives promise unprecedented properties and performance, e.g., incorporation of biocides in coatings to produce self-cleaning surfaces, or addition of nanoparticles to cosmetics to improve feel, wear, and anti-aging effects.

***Economic Significance of Innovation*:** The majority of manufactured goods are so-called "formulations," products that are fabricated from a large number of components. Formulated products include paint and coatings, food, cosmetics, personal care products, and cleaning products among many others. Most often, the market for formulated products is driven by the ability to produce specialty materials with improved performance and tailored specifications, while reducing cost. Formulated complex fluids represent a large global market worth more than $150 B per year. The next generation of these products will possess value added by nanoscale components. Without the competitive edge to enable this innovation in the United States, enormous market share will be lost to competitors.

***Technical Barrier to the Innovation*:** The design and optimization of complex fluid formulations is an "art", which relies on individual knowledge to combine compiled experience and "trial-and-error" methods to arrive at optimal products. While many industries use formulation techniques in making and testing their products, there is no formal discipline in formulations based on first principles. Understanding interactions between nanostructured additives and complex mixtures, particularly the relationship between phase behavior, morphology, stability, and performance properties, including possible health effects is critical. However, there is no fundamental measurement platform on which to build the nano-metrology necessary to characterize the next generation of materials.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The performance and safety of these products depends on reliable nanomaterial feed stocks, robust processing methods and the stability of end products. Current formulation science has not advanced enough to handle these measurements, due to a historical reliance on individual knowledge and a lack of quantitative data collection or standard measurements.

***Potential Solutions to Measurement Problem*:** Standard reference materials and new measurement methods to quantify purity, characterize quality, monitor processes and measure stability are necessary. For example, a high throughput platform to evaluate the solution properties of peptidic interfacial modifiers in the presence of other surfactants, changes in pH, salt and temperature using a combination of scattering, spectroscopy and imaging techniques would be integrated with evaluations of end-use properties, such as biocide activity, vector delivery, etc.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Advanced Scanning Probe Microscopy

***Submitter*:** Michael J. Fasolka

***Technological Innovation at Stake*:** Innovation in nanomaterials and nanodevices requires means to gauge performance, verify fabrication routes and ensure quality control in new products. Advanced scanning probe microscopy (SPM) techniques have great potential for nanoscale mapping of the chemical, mechanical, thermal and electro-optical properties inherent to new nanotechnology products. However, these emerging SPM methods will not provide the information required for new product development, and thus will not enable nanotechnology innovation, unless they provide quantitative data.

***Economic Significance of Innovation*:** Nearly every US industrial lab involved in nanotechnology development has purchased basic SPM instrumentation because it provides routine, cost-effective nanoscale imaging of product topography. Advanced SPM will allow industry to apply this infrastructure investment (perhaps $1.5B since 1999) towards the analysis of the properties that increasingly govern the performance and quality of new nanotechnology products. This savings would be especially important among small and medium sized businesses, which depend upon the cost-effective analysis of SPM. Moreover, for the SPM instrumentation industry, projected growth to $1.2B/yr by 2007 depends upon their ability to produce robust, innovative measurement solutions for new nanomaterials applications.

***Technical Barrier to the Innovation*:** While proposed new SPM approaches are promising, generally they do not provide the quantitative measurements required for new nanomaterials development and commercialization. By and large, this is due to the fact that these techniques depend upon custom made or proprietary probes, the fabrication of which is often not reliable or uniform. In addition, certain probe characteristics must be known in order to quantify image data. Moreover, advanced SPM data is governed by a set of sample/probe interactions that are complex and often not understood. Finally, there is currently no means to compare SPM data collected from different instruments and/or probes.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Quantification of SPM image data requires measurements to characterize the size and quality of new probe types, gauge instrument resolution and sensitivity, reliable probe manufacture, and means for weighing the many factors that contribute to advanced SPM data.

***Potential Solutions to Measurement Problem*:** Reference specimens and materials, designed to gauge probe quality and characteristics, lateral image resolution, and probe sensitivity. Best practices and quality standards for advanced probe manufacture. Standard protocols for advanced SPM data collection. Models of probe-surface interactions for describing advanced SPM data.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** 2nd Generation Lightweight Armor

***Submitter*:** Gale A. Holmes

***Technological Innovation at Stake*:** New classes of body armor are under development using fibers whose ballistic mechanical properties exceed those of the Kevlar fibers used in the majority of ballistic resistant ("bulletproof") armor.

***Economic Significance of Innovation*:** Based on the cost of current non-Kevlar options of $1,000 per vest and a police force exceeding 700,000 personnel, the manufacture of lightweight body armor is easily a $1B industry. Kevlar body armor is heavy, inflexible, and uncomfortable. By using higher performance materials, the same level of ballistic protection can be maintained while reducing the weight of the armor. The reduced weight also increases the flexibility and comfort level of the armor and makes it more concealable. Also, it can save lives, increasing the performance of law enforcement activities through this better protection.

***Technical Barrier to the Innovation*:** With all the promise of these new fibers, their long-term environmental durability (i.e., humidity, temperature, and UV) and reduction in performance due to normal use folding are unknown in advance, thereby impeding new fiber implementation in ballistic resistant applications. In the absence of this information, recommended care guidelines to ensure continued protection are non-existent for the armor.

***Stage of Innovation Where Barrier Appears*:** R&D and End Use

***Measurement-Problem Part of Technical Barrier*:** Excluding the destructive V-50 ballistics test, reliable methods are unavailable for characterizing environmental or mechanical degradation. Measurement methods are needed for characterizing the fiber degradation and potentially for in-service monitoring of the armor. With such methods, recommended care guidelines could be established and in-service armor could be evaluated non-destructively for verification of continued protection of the wearer.

***Potential Solutions to Measurement Problem*:** Potential solutions include development of minimally invasive techniques for characterizing the ballistic resistant properties of the fibers, e.g., the NIST-developed modified single fiber test or small angle x-ray scattering techniques; characterization of the degradation pathways and products to enable spectroscopic monitoring of degradation; and development of methods to quantify the impact of mechanical fatigue, e.g., folding.

Case Study – Measurement Needs

***Technology at Issue*:** Machine Readable Travel Documents (MRTDs) (focus on electronic passports)

Submitter: Walter McDonough

Technological Innovation at Stake: The Border Security Act requires that countries whose citizens may enter the U.S. under the Visa Waiver Program (VWP) issue passports that incorporate biometric identifiers that comply with standards established by the International Civil Aviation Organization (ICAO) by October 26, 2004. This represents a dramatic technological change from the existing passports, both from a structural and an electronic side. The benefits of the proposed change will be in the enhanced security and control over the documents. The durability of MRTDs needs to be guaranteed since the MRTDs are required to last for ten years. Currently, no method exists for assessing the long term durability and performance of MRTDs.

***Economic Significance of Innovation*:** Each new U.S. electronic passport will cost approximately This year, the Government will process approximately 13 million passports, and this number is expected go up to 17 million next year and 21 million in two years because of new regulations regarding leaving and entering the United States (Western Hemisphere Travel Initiative). This then will amount to $2 billion/year for passports that are required to last ten years. Any required replacements before the ten year period is up will add to that cost (to the government and taxpayer) in proportion.

***Technical Barrier to the Innovation*:** The chief technical barrier from a durability standpoint is that there are no standards to assess or estimate the performance over the anticipated ten year lifespan of these documents. The difficulty comes from the fundamental changes in the physical composition of these documents. Since there is no base line, we do not know how much the presence of the electronic components has strengthened or weakened the books.

Stage of Innovation Where Barrier Appears: R & D and Production

***Measurement-Problem Part of Technical Barrier*:** No durability test methods exist to assess the long term durability and performance of MRTDs, such as the electronic passport. This is not the problem for a single nation to solve, but rather for all nations within the International Civil Aviation Organization (ICAO). A unified international test standard is needed, preferably through ISO/IEC/JTC1/SC17/WG3/TF4, but a large challenge stems from the fact that test methods are being developed as products are being developed. Since the product and test method are being developed simultaneously, there is nothing to measure against.

Potential Solutions to Measurement Problem: Development of appropriate durability and performance testing methods that have been rigorously assessed through international round robin testing and evaluation.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Nanoscale Integrated Circuits: Dimensional Control

***Submitter*:** Eric K. Lin, Wen-li Wu

***Technological Innovation at Stake*:** The production of integrated circuits with nanoscale device structures is needed for the continued increase in cost to performance of integrated circuits; 20 nm by 2009 and 10 nm by 2013. Continued progress in the semiconductor industry depends upon the ability to manufacture designed patterns with sub-50 nm dimensions with sufficient dimensional control and resolution. To do this on a manufacturing scale, new sophisticated process control methods that include structure and device inspection are needed because current solutions are not sufficient.

***Economic Significance of Innovation*:** The semiconductor industry is a significant driving force in the U.S. economy through the continued price per function that arises from the fabrication of ever smaller structures, which can result in products that are smaller, cheaper, and with more functionality Lithography, including dimensional metrology currently comprises 30 to 40 % of the entire cost of semiconductor manufacturing, a several billion dollar enterprise. The continued economic success of the semiconductor industry depends upon capabilities to control device dimensions at nanometer length scales.

***Technical Barrier to the Innovation*:** Current methods such as scanning electron microscopy (SEM) and optical scatterometry face significant challenges to provide the needed nondestructive, production-worthy wafer and mask-level measurement of nanoscale critical dimensions, line-edge roughness, interfacial structure, and defect levels of complex 3D structures. These challenges become more difficult as new materials such as those with low-dielectric constant (k) that require additional structural information (porosity), or extreme ultraviolet photoresists that degrade when exposed to electron beams are introduced into production.

***Stage of Innovation Where Barrier Appears*:** R&D, Production

***Measurement-Problem Part of Technical Barrier*:** Rapid, on-line, non-destructive measurements of the structure of densely patterned features such as gates and trenches with their smallest, or "critical", dimensions < 40 nm and a roughness of < 1 nm. This level of inspection is important because variations in feature size of one tenth of the nominal dimension often results in significant changes in device properties.

***Potential Solutions to Measurement Problem*:** A high precision X-ray based measurement method, Critical Dimension Small Angle X-ray Scattering (CD-SAXS) may provide a solution. This technique is capable of non-destructive measurements of test patterns used by microelectronic industries to monitor their fabrication process. CD-SAXS measurements performed at synchrotron facilities have successfully demonstrated the potential capability for sub-nm precision for periodicity and line width measurements and initial characterization of line-edge roughness. Challenges remain to enable this technology at production lines and in-house laboratories including the development of sufficiently bright sources in a compact form.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Nanoimprint Lithography (NIL)

***Submitter*:** Christopher L. Soles

***Technological Innovation at Stake*:** To date, all lithography tools capable of patterning with 5 to 10 nm resolution, write serially with a beam spot size that is also 5 to 10 nm. These techniques are extremely slow, very costly, and not suitable for high volume manufacturing. NIL is rapidly emerging as a nanoscale replication technique, capable of producing high resolution copies of nanoscale patterns fabricated over large areas at production speeds that approach multiple wafers per minute. This seminal advancement in mass production lithography has the potential to bring high volume nanotechnology to the commercial marketplace in markets extending from the semiconductor industry and beyond.

***Economic Significance of Innovation*:** NIL tools are relatively inexpensive, ranging from $100K to $1M This is a fraction of the cost of the current state of the art high volume lithography tools that cost upwards of $25M to $50M. For this reason the semiconductor industry is pushing hard to integrate NIL capabilities into their production infrastructure. At the same time, the low cost of the NIL technique is making high resolution patterning a reality for small, high tech business in the nanotechnology arena. For these reasons MITs Technology Review (Feb, 2003) identified NIL as one of the 10 emerging technologies that will change the world by making nanomanufacturing a reality.

***Technical Barrier to the Innovation*:** Our ability to create patterns now exceeds our ability to quantify, evaluate, or measure the quality of the new nanoscale metrologies needed to help evaluate and optimize NIL processes to the level required for commercial applications. Current electron beam inspection tools are being improved in terms of their throughput and resolution. Scanning probe techniques are also being adapted for more accurate measurements. Both of these solutions require significant efforts in calibration and tractability. Optical techniques are also being considered but require extensive model libraries to yield quantitative parameters. All of these techniques have great difficulties in characterizing densely packed or buried nanostructures.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Critical dimension (sample shape) metrologies that are non-destructive and offer sub-nm resolution are critically needed to optimize NIL materials, process, and products. The International Technology Roadmap for Semiconductors clearly states viable solutions to critical dimension metrologies at the patterning length scales achievable by NIL do not exist.

***Potential Solutions to Measurement Problem*:** X-ray scattering and reflectivity techniques are generating interest because of their ability to characterize very small patterns non-destructively. NIST has recently developed Critical Dimension Small Angle Scattering (CD-SAXS) as one such alternative. Because of its potential, CD-SAXS will be included in future versions of the ITRS Roadmap as a candidate next generation metrology.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Self Assembly of Soft Nanomaterials

***Submitter*:** Steven Hudson

***Technological Innovation at Stake*:** The use of directed self-assembly in chemical, electronics, and pharmaceuticals industries to produce smart coatings, detergents, personal care products, (photovoltaic) circuits, and targeted drugs. Self-assembly, or bottom-up assembly, proceeds from the nano or molecular scale and is driven by natural interactions. To make practical devices on the nanoscale, directed self-assembly techniques that allow the assembly of complex systems composed of large numbers of nanoscale components will be necessary. Anticipated benefits of directed self assembly include smarter targeting and product design, enabling structures with greater functionality that tend to be defect-free and self-healing.

***Economic Significance of Innovation*:** Self assembly is prominent in a US chemical industry roadmap (www.ChemicalVision2020.org) that outlines a strategy to develop knowledge and tools that will alter management of the industry's $26B annual R&D investment and enable application-based design and pervasive use of nanomaterials. Current examples of self assembly are found in colloidal technology (e.g., washing detergent formulations) and pharmaceuticals (drug formulations). Future opportunities such as micro-injectable computer-chip heat-transfer fluids and virus-based drug delivery require the development of directed self assembly, which will enable smarter targeting and product design.

***Technical Barrier to the Innovation*:** Although man-made self-assembled nanomaterials do exist, they are still generally simple and poorly controlled. It is difficult to "order-up" a complex functional structure from simpler components because the needed interactions between the sub-components are not known.

***Stage of Innovation Where Barrier Appears*:** R&D and production

***Measurement-Problem Part of Technical Barrier*:** In order to develop well controlled self-assembled materials, we need the ability to measure the forces between the components or particles during the assembly process and measure the rates of assembly (and disassembly). Particle characterization methods (e.g., to measure the surface charge distribution) are necessary to ensure quality control. Further, rapid measures of the actual self-assembled structures and their response to stimuli (such as agitation, pH or temperature) are vital to establish design rules.

***Potential Solutions to Measurement Problem*:** The measurement of interparticle forces by surface spectroscopic and microscopic methods will enable improved control over the assembly process and the measure of local and average assembly kinetics. Rapid screening methods by indirect scattering, direct visualization, and property measurements will enable quality control and process control. Efficient computational methods informed by these measurements will allow the development of design rules.

Case Study – Measurement Needs

***Technology at Issue*:** Sub-50 nm Lithography Materials

***Submitter*:** Vivek M. Prabhu

***Technological Innovation at Stake*:** The production of smaller device structures for the continued improvement in cost to performance of integrated circuits is at stake: 20 nm by 2009 and 10 nm by 2013. Continued progress in the semiconductor industry depends upon the ability to develop materials capable of manufacturing designed patterns with sub-50 nm dimensions with sufficient dimensional control and resolution.

***Economic Significance of Innovation*:** The semiconductor industry is a significant driving force in the U.S. economy and the lithography process is a major part of the cost of manufacturing integrated circuits. Lithography, including dimensional metrology currently comprises 30 to 40 % of the entire cost of semiconductor manufacturing, a several billion dollar enterprise. The continued rate of the economic success of the semiconductor industry depends upon ability to fabricate ever smaller device dimensions.

***Technical Barrier to the Innovation*:** It is unknown whether apparent limitations in the patterning ability of current materials for industrial nanofabrication, chemically amplified photoresists, are intrinsic material resolution limits (line-edge roughness of 4 nm) or can be improved with better optics and process control. Maintaining the rapid pace of shrinking dimensions requires significant improvements in optical projection lithography technology or the development of alternative, next generation lithography technologies.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** At nanoscale dimensions, the details of local materials properties and physico-chemical processes affect the resolution of the lithographic process. Current measurement methods do not provide the spatial resolution or chemically specific information needed to carefully probe process parameters that limit the patterning resolution and to inform potential solutions. There are too many variables including the specific formulation of a multicomponent material, dose, post-exposure bake conditions, or developer concentration to depend on the success of trial-and-error improvements.

***Potential Solutions to Measurement Problem*:** Integrated measurements that can provide unique information about complex physico–chemical processes used in advanced chemically amplified photoresists. Methods include x-ray and neutron reflectivity, near-edge x-ray absorption fine structure spectroscopy, and quartz crystal microbalance measurements. With this information, better physical/chemical models can be developed to predict three-dimensional resist geometries after development and process windows, including effects such as line-edge roughness.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Tissue-Engineered Medical Products (TEMPS) In Vivo Monitoring

***Submitter*:** Marcus Cicerone

***Technological Innovation at Stake*:** The creation of man-made tissues or organs through tissue-engineered medical products (TEMPs), constitutes an exciting, relatively new approach that has potential to revolutionize the treatment of many injury and disease states. Approaches range from enhancing regrowth of tissue to stimulating regrowth of an entire organ. In most cases, biodegradable polymers are used as a scaffolding to guide tissue and organ regeneration.

***Economic Significance of Innovation*:** It is expected that the potential economic impact of the Tissue Engineering field will be very large. Diabetes mellitus, a primary target condition, has estimated annual direct and indirect costs of nearly $120 billion -including secondary illnesses. This accounts for more than 10 percent of the nation's total annual healthcare costs. In the cardiovascular arena, the ability to regenerate heart muscle or provide tissue engineered blood vessels will save billions and significantly increase quality of life while reducing morbidity and mortality rates. The NIST ATP program estimates that tissue-engineered livers alone could save more than $140 million / year assisting chronic and acute liver failure patients. Tissue-engineered articular cartilage will limit knee replacements for thousands in the U.S., improving worker productivity and increasing quality of life.

***Technical Barrier to the Innovation*:** Both manufacturers and regulatory agencies are often uncertain as to how to quantify performance and specifications of TEMPs. The difficulty in establishing such specifications has its root in insufficient understanding of the fundamental mechanisms behind the ability to regenerate tissue in vivo, or in vitro. TEMPs are typically evaluated using destructive, endpoint testing methods. These are time-consuming and necessarily involve loss of information. Noninvasive in vivo imaging modalities continue to hold promise towards ameliorating the difficulty of TEMPs evaluation.

***Stage of Innovation Where Barrier Appears*:** R&D, Production, End Use

***Measurement-Problem Part of Technical Barrier*:** An adequate measurement infrastructure does not exist for this industry because it is still in its infancy. This impacts research, manufacturing, and regulatory issues, and must be rectified. A recent FDA Critical Path document concisely stated the problem: “Additional characterization procedures and standards for …other cellular products, bioengineered tissues, and implanted drug-device combinations …are urgently needed.” High information-content methods, such as hyperspectral imaging (e.g. CARS microscopy) are of particular promise.

***Potential Solutions to Measurement Problem*:** International standards organizations, including ASTM and VAMAS recognize the need for standards and reference methods for TEMPs. They have recognized that this can be best accomplished by development of **non-invasive, quantitative imaging methodologies,** which can be used as bases for standard protocols, and with which products can be non-destructively evaluated in comparison to reference artifacts and benchmarks before and after placement.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Engineered Surfaces for Reduced Friction Applications

Submitter(s): Stephen Hsu

Technological Innovation at Stake: Machinery (particularly heavy machinery) manufacturers are improving fuel efficiencies, increasing power-to-weight ratios and minimizing environmental pollution through reductions in friction between bearing surfaces in relative motion. Such reductions are achieved by creating surface textures of specific geometry and profile to control contact area, frictional characteristics, interfacial temperatures, and contact stress distributions. Recent advances in surface micro-machining, laser texturing and directional coating techniques make possible such designed surfaces for use on parts in engine cylinders, roller bearings and other rotating and sliding parts. However, these advantages are achieved at the high cost because a specified texture is difficult to replicate between fabrication machines and sites.

***Economic Significance of Innovation*:** Projected estimates of up to 28% increase in automobile fuel economy may be achievable if engine friction were completely eliminated: Friction reducing textured surfaces in cam lifters, gears, transmissions could provide up to 5% improvement in fuel economy. Honda Motor Co. last year introduced a textured piston skirt and claimed 2.5% improvement in fuel economy. If translated to the U.S. auto fleet, this amounts to ~$7B/yr @ ~$2/gal., based on 2005 U.S. total gasoline consumption. In bearings and axle applications, textured surfaces reduce friction and thus increase load-bearing capacity and hence extend component life.

***Technical Barrier to the Innovation*:** Multi-length scale measurement techniques and adequate descriptors to characterize textured surfaces are largely absent, leading to an inability to characterize surface structure that inhibits structure-property linkage formation to guide manufacturing of high-performance, low-friction surfaces. Different companies and different countries produce a wide variety of textured surfaces by various fabrication techniques. In order to remove barriers to domestic and international trade standardized measurement methods for comparison of textured surfaces and their benefits are required. Texturing introduces discrete features that traditional surface roughness parameters are inadequate to characterize (previous surface descriptors are based on statistical measures.)

Stage of Innovation Where Barrier Appears: Production

***Measurement-Problem Part of Technical Barrier*:** Tools for rapid 3-D measurement of multi-scale features on textured surfaces with sufficient accuracy and precision over large surface areas is lacking. Characterization of texture on piston rings and cylinder liners requires a tool to measure features from nanometer to millimeter scales on interior and exterior curved surfaces over areas of 100 mm^2. Descriptors of the complex textured surfaces are lacking.

Potential Solutions to Measurement Problem: Through an industrial and international partnership, a compilation of current techniques for characterizing textured surfaces will be a first step in establishing a common language in trade. Research and development is required to generate adequate surface descriptors and instrumentation to scan rapidly with lateral resolution less than 100 nm.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Advanced CMOS Gate Stacks for Next Generation Integrated Circuit Devices

***Submitter*:** Martin Green

***Technological Innovation at Stake*:** Further scaling (dimensional shrinkage of integrated circuit device elements according to Moore's Law) in Si microelectronics is presently limited by a lack of new materials to replace the gate stack layers. A material with a dielectric constant greater than about 20 is needed to replace the SiO_2 (dielectric constant ~3.9) gate dielectric, and a metal is needed to replace the degenerately doped poly-crystalline Si gate electrode.

***Economic Significance of Innovation*:** The silicon microelectronics industry, and the consumer electronics and information revolution that it fuels, is, at $750 billion, one of the largest sectors of the global (and US) economy. Continued innovation in Si microelectronics is of immense importance.

***Technical Barrier to the Innovation*:** The gate stack of CMOSFET (complementary-metal-oxide -silicon-field-effect-transistor, the workhorse of advanced chips such as Pentium microprocessors) transistors poses a complex materials science issue. Well over 10,000 papers have been devoted to it since Si integration began in the late 1960's. Now, for the first time, materials native to and compatible with Si (SiO_2 and poly-crystalline Si) are being replaced; the introduction of new gate dielectric and gate electrode layer materials requires an entirely new understanding of, for example, interfacial stability, as well as the effect of processing variables on electronic properties such as work function and interface state density. Further, the required research effort is greatly multiplied by the wide choice of candidate materials identified for both applications.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** There are two aspects to the measurement problem—identification of techniques, and the number/speed of measurements that are needed. First, for some measurements, such as work function, identifying the most appropriate measurement is not even clear. Second, even for known measurement techniques, it is imperative to be able to make hundreds or thousands of measurements at once, since there are at least that many combinations of gate dielectric and metal electrode materials compositions that need to be assessed for each material system considered.

***Potential Solutions to Measurement Problem*:** Combinatorial materials science methodologies offer great promise to identify classes of materials, layer compositions, and multilayer (gate stack) combinations that are both thermally stable, and possess the required electronic characteristics. New high-throughput, combinatorial measurement techniques, such as nano-calorimetry to measure thermal stability, and capacitance-voltage to derive the metal-semiconductor work function, must be devised.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Flip Chip Packaging Materials

***Submitter*:** Christopher M. Stafford

***Technological Innovation at Stake*:** Flip chip interconnect technology is the smallest form of electrical interconnection and is driving the miniaturization of devices in the microelectronics industry. This technology relies on underfill materials that impart thermal cycling reliability, environmental stability, and mechanical strength of the package. To meet shrinking form factors and more stringent reliability requirements, materials suppliers and materials users require measurement strategies and capabilities that will enable them to keep pace with accelerated development timelines and shortened time to market.

***Economic Significance of Innovation*:** Market researchers forecast unit volumes of high-end advanced packages such as flip-chip chipsets and graphics processors to increase from $112M in 2003 to $430M in 2008. According to a study by SEMI and TechSearch International, the market for semiconductor packaging materials is expected to grow from $14.0B in 2006 to $19.5B by 2010, with underfill materials alone expected to increase from $122M in 2006 to $331M in 2010. The innovation will have direct impact on semiconductor device manufacturers (e.g., Intel, Motorola, IBM, AMD), packaging foundries that serve the semiconductor sector (e.g., Amkor, ChipPac, AIT), and materials suppliers (e.g., Cookson, National Starch, Henkel Electronics).

***Technical Barrier to the Innovation*:** Failure in packaging severely limits the reliability and lifetime of semiconductor devices, particularly in flip chip interconnect technology. Delamination of cured underfill material from the die and/or substrate interface due to internal and external stresses is considered one of the most serious failures, where the delamination event escalates under thermal cycling until it fractures a component of the solder bump array. Rapid, quantitative assessment of the mechanical behavior of underfill materials will allow a broad set of complex, innovative microelectronic products into the market faster.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Quantitative high-throughput measurement techniques for assessing the adhesion and durability of combinatorial underfill libraries do not exist. These materials systems can exhibit extremely complex mechanical behavior, including difficult to predict cooperative and parasitic effects, that traditional "one at a time" measurement strategies often overlook and/or neglect due to limitations in resources and time. This requires new and clever approaches for producing combinatorial libraries of interest, as well as a high-throughput metrology for gauging the performance of the types of interfaces encountered in advanced packaging. The design and validation of such a measurement platform is a considerable technological challenge for industry.

***Potential Solutions to Measurement Problem*:** R&D to develop a deposition system capable of handling moderately viscous and highly filled underfill materials for fabricating combinatorial libraries for testing. Development of a combinatorial and high-throughput testing platform that accommodates/ incorporates appropriate library design, material handling requirements, and necessary experimental uncertainty. Advance quantification and knowledge through finite element modeling.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Biomimetic Regenerative Materials in Dental Applications

***Submitter*:** Lin-Gibson and Antonucci

***Technological Innovation at Stake*:** Bioactive and regenerative polymers and composites have potential to be used to arrest and reverse tooth caries and bone loss. Successful development will provide a new and effective regimen for the treatment of hard tissue diseases and traumatic injuries.

***Economic Significance of Innovation*:** The Center for Disease Control reports that over 40 % of children between 5 and 17 years of age and many adults have dental caries (tooth decay). Treatments and replacements based on existing technology for dental applications alone amounts to billions of dollars each year in the US. The therapeutic benefits of preventing caries development and extending the clinical lifetime of dental fillings have significant impact in human health and non-quantifiable benefits, such as the confidence better oral health provides. Because similar classes of materials are involved, these technologies are also expected to greatly benefit other areas of biomedical applications such as orthopedics.

***Technical Barrier to the Innovation*:** This technology is in early stages of development. With the present level of scientific understanding, biological response to polymeric materials in complex physiological environments is difficult to predict. An outstanding need exists for work relating chemical structure and functional properties of materials to biological response. Increased knowledge and understanding of the structure-function relationships controlling rejection of or compatibility with synthetic materials by the natural biological materials of the body will be the basis for filling the current need for rational- materials design that induces biological regeneration.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Currently, only a small number of groups are developing test models for understanding and predicting the effectiveness of bioactive and regenerative polymers in caries. Most of these do not provide insights into temporal or spatially dependent mechanisms and are gross simplification of the complex physiological environment. There is a need for measurement techniques capable of correctly characterizing in vivo biological response to materials. Such techniques must capture reliable time-dependent regenerative characteristics. Improved measurement approaches for direct observation of mineralization kinetics and mechanisms can significantly increase new knowledge relating chemical structure of materials and biological response to them.

***Potential Solutions to Measurement Problem*:** Test platforms to accurately model various physiological environments found in healthy and diseased tissue are needed. New techniques for incorporating caries causing bacteria within the plaque such as streptococcus mutans should be incorporated. Measurements coupled to the device should include ion electrode analysis, state-of-the-art imaging techniques, and bio-assays.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Advanced Specialty Materials

***Submitter*:** Michael J. Fasolka

Technological Innovation at Stake: Innovation in technologies such as advanced electronics, functional coatings, biomedical products, personal care products, protective gear, MEMS/NEMS and sensors, hinges on the discovery and optimization of new materials. To sustain the pace of innovation in these other fields, industry strives to develop advanced specialty materials (e.g., nanostructured materials, organic electronics, semiconductors, intelligent materials and biomaterials) for these applications more rapidly and efficiently.

***Economic Significance of Innovation*:** Research and development of new materials costs US industries approximately $20B/year. Using traditional approaches, the time to discover a new material ranges from 2 to 10 years, with R&D costs often in excess of $20M per new material product. However, If the high R&D cost of developing new materials can be reduced, it can have large impacts in many different (and unforeseen) economic sectors. Indeed, estimates predict that by using combinatorial and high-throughput methods, new materials can be generated in 0.5 to 2 years apiece and at 1/5 the cost of traditional methods.

***Technical Barrier to the Innovation*:** The properties of specialty materials depend on an enormous number of compositional and processing parameters, while their target applications entail highly specific performance criteria. Accordingly, the discovery and optimization of these materials requires that a massive number of experiments be conducted. If industry continues to rely on traditional "one-at-a-time" experimental approaches, materials discovery will remain slow, difficult and expensive.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Traditional measurements of materials properties and performance are simply too slow. To accommodate the huge number of measurements inherent to specialty materials R&D, industrial researchers hope to adapt and implement combinatorial and high-throughput (C&HT) measurement approaches similar to those used in the pharmaceutical industry for drug discovery. However, for most cases, C&HT measurement methods suited for the discovery and optimization of cutting edge materials systems – where innovation is high – do not exist. In addition, most companies wishing to implement C&HT measurement methods for materials research need guidance about how to do so.

***Potential Solutions to Measurement Problem*:** Development of robust, open source, C&HT measurement methods and instrumentation expressly geared towards advanced specialty materials R&D. Determination of best practices in C&HT approaches. Practical guidance on the implementation of C&HT methods. Data interchange standards for C&HT informatics workflows.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Nanomanufactured Components

***Submitter*:** Ronald Jones

***Technological Innovation at Stake*:** Emerging nanotechnologies for microelectronics, data storage, and bio-agent sensors are based on large area substrates patterned with trillions of nanometer scale components. In the case of data storage, the switch from uniform magnetic films to arrays of nanostructures will increase data density from ≈ 10 Gb/in^2 to > 100 Gb/in^2. Increases in areal density will facilitate a range of high storage applications (i.e. medical records, digital video cameras).

***Economic Significance of Innovation*:** The data storage market alone is projected to increase 35% in 2006 based on the emergence of high density drives for consumer products, while the multibillion dollar micro-electronic industry is moving toward patterning of sub-50 nm features by 2007. In each of these markets, products will feature macroscopic areas patterned with dense arrays of nanostructures.

***Technical Barrier to the Innovation*:** In applications requiring dense arrays of nanostructures, the small dimensions of the structures will require sub-nm tolerances in positional placement. Current methods of manufacturing are not capable of consistent structural placement on this scale. As a result of the low cost of the final product, nanomanufacturing will need to inspect trillions of nanometer scale components at high speeds, identifying defects such as voids at early stages in production to be economically viable.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The primary measurement challenge is the "needle in a haystack" issue. The problem requires techniques to search macroscopic areas, a single nm at a time to find errors in size and shape of nanostructures. As an example, a single 50 nm void within a 50 nm wide insulating layer in state of the art microelectronic circuits can lead to short circuits and device failure. A typical circuit design can feature a mile of insulating layer length, challenging all existing platforms for defect inspection

***Potential Solutions to Measurement Problem*:** Development of size- and shape-sensitive nanoprobes may provide a massively parallel optical measure of defect location across large areas. Other possibilities include the use of sub-wavelength optical probes and large area x-ray microscopy to identify "defective zones" that limit the area of searching for higher resolution imaging techniques.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Directed Nanoscale Assembly

***Submitter*:** Vivek M. Prabhu, Eric K. Lin

***Technological Innovation at Stake*:** Controlling the placement of nanoscale units into designed structures and patterns through directed self-assembly processes; a grand challenge of nanotechnology. Self-assembly could enable the applications of the unique properties of nanoscale materials and structures with fabrication methods (in water or with biological materials) well-matched with exciting new applications.

***Economic Significance of Innovation*:** Directed assembly would facilitate nanofabrication of materials and applications orthogonal to those in the traditional semiconductor sector that could include biological functionality such as active biosensors or new devices such as large-area, flexible electronics. For example, in nanoscale electronics, the markets for nanomaterials, tools and equipment totaled approximately $1.8 billion in 2005 and are forecasted to reach nearly $4.2 billion by the year 2010. These applications open new markets with potential devices that currently do not exist.

***Technical Barrier to the Innovation*:** Directed self-assembly processes for the production of novel materials and devices have been demonstrated at a limited scale. However, these processes have not been developed in the context of large scale manufacturing or production. The infrastructure to determine objectively if the components can be self-assembled with sufficient fidelity and reproducibility has not been developed. Nanoscale materials suppliers and product developers will need a common set of metrics and methodologies to develop new technologies and facilitate commerce.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** New evaluation criteria and metrics unique to nanoscale directed assembly are needed to reach manufacturing design requirements. These quantities include selectivity, specificity, and registry of nanoscale building blocks. These quantities have been developed for biological assay such as in the development of DNA microarray technology, but new measurements, methodologies, and definitions are needed to quantify and validate nanoscale assembly to ensure confidence in their use in a manufacturing environment.

***Potential Solutions to Measurement Problem*:** Initially, validation methods and concepts developed for biological technologies such as protein affinity or DNA microarrays may be adopted and adapted. For 1-D directed assembly of particles to surfaces and interfaces, quartz crystal microbalance (QCM) measurements can be combined with evanescent-wave fluorescence correlation spectroscopy (FCS) and fluorescence-resonance energy transfer (FRET) to probe assembly over a (2 to 10) nm length scale and a (100 ns to s) time scale. Selectivity can be quantified by comparing results on well-characterized material surfaces. New model test patterns in combination with fluorescence detection can be developed to evaluate selectivity, specificity, and registry of building blocks into fabricated, designed templates.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Materials-Guided Tissue Regeneration

***Submitter*:** Marcus Cicerone

***Technological Innovation at Stake*:** The creation of man-made tissues or organs through tissue-engineered medical products (TEMPs), constitutes an exciting, relatively new strategy that has potential to revolutionize the treatment of medical treatment of many injury and disease states. Approaches range from enhancing regrowth of tissue to stimulating regrowth of an entire organ. In most cases, biodegradable polymers are used as a scaffolding to guide tissue and organ regeneration.

***Economic Significance of Innovation*:** The potential economic impact of TEMPs is potentially very large and has three main components: improved human health, increased biomedical knowledge, and reduced health care costs. It is expected that the potential economic impact of the Tissue Engineering field will be very large. Diabetes mellitus, a primary target condition, has estimated annual direct and indirect costs of nearly $120 billion -including secondary illnesses. This accounts for more than 10 percent of the nation's total annual healthcare costs. In the cardiovascular arena, the ability to regenerate heart muscle or provide tissue engineered blood vessels will save billions and significantly increase quality of life while reducing morbidity and mortality rates. The NIST ATP program estimates that tissue-engineered livers alone could save more than $140 million / year assisting chronic and acute liver failure patients. Tissue-engineered articular cartilage will limit knee replacements for thousands in the U.S., improving worker productivity and increasing quality of life.

***Technical Barrier to the Innovation*:** Because quantitative performance metrics are lacking, manufacturers, users, and regulatory agencies are often uncertain as to how to characterize performance and specifications of TEMPs, making managing in vivo monitoring problematic and, at times, ineffective. There are two interrelated barriers: 1) gaps in fundamental, application-specific knowledge of cellular response to materials surface functionality and 2) the ability to precisely engineer/process synthetic materials to have desired surface properties,

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** An adequate measurement infrastructure does not exist for this industry because it is still in its infancy. This impacts research, manufacturing, and regulatory issues, and must be rectified. A recent FDA Critical Path document concisely stated the problem: "Additional characterization procedures and standards for …other cellular products, bioengineered tissues, and implanted drug-device combinations …are urgently needed."

***Potential Solutions to Measurement Problem*:** International standards organizations, including ASTM and VAMAS recognize the need for measurement standards and reference methods for TEMPs. They have recognized that this can be best accomplished by development of **non-invasive, quantitative imaging methodologies,** which can be used as bases for standard protocols, for development of improved scientific understanding of TEMP rejection by and compatibility with the body, and for non-destructive evaluation relative to reference artifacts and benchmarks before and after placement.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Next-Generation Active Nanodevices

***Submitter*:** Chad Snyder

***Technological Innovation at Stake*:** Next generation active, i.e., powered, nanodevices will enable greater functionality (e.g., faster computations, larger memory storage, or combinations thereof) in smaller packages, providing the basis for a broad range of high tech products. A broad range of new products will be impacted, e.g., components of integrated circuits, NEMS, and optoelectronic devices.

***Economic Significance of Innovation*:** As an example of the economic significance of this innovation, the U.S. Department of Commerce's Bureau of Economic Analysis estimates the domestic semiconductor and related devices industries' gross output to be $80B in 2004. To keep up with Moore's law and to maintain or grow the output level of this industry, next generation devices must be developed.

***Technical Barrier to the Innovation*:** One of the barriers to this innovation is heat dissipation, i.e., the problem of thermal management. The 2003 ITRS indicates that the task of dissipating heat from nanodevices will significantly increase in the future due to increasing power, decreasing junction temperatures, and a continuing need to have cost-effective solutions. Many MEMS applications demand an inert or vacuum environment inside the package, eliminating the possibility of air cooling and making thermal management even more critical; and optoelectronic devices have temperature sensitivity in their operating parameters, such as wavelength. Additionally, there will be thermal management problems with emerging devices such as NEMS, quantum cellular automata, cellular nonlinear networks, biologically inspired architectures, and coherent quantum computing; predictive capabilities for the behavior of these systems are currently model and input data limited.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Thermal conductivity/diffusivity in complex geometries and at the nanoscale requires measurement techniques beyond the current state-of-the-art. Further, measurements that can provide insight into the effects of defects, interfaces, and molecular anisotropy on the thermal characteristics of nanodevices are critically needed. Existing characterization techniques are designed to characterize bulk materials or films on substrates and therefore cannot address issues such as spatial confinement of photons at the nanoscale and thermal boundary resistance (which is a function of defects and interfaces) between multiple structures.

***Potential Solutions to Measurement Problem*:** R&D to find practical way to extend the capabilities of current measurement instrumentation, e.g., the widely accepted 3ω technique for direct measurement of thermal conductivity, and to develop appropriate testbeds, with controlled defects, interfaces, molecular anisotropy and 3D geometries, which allow quantification of nanoscale effects, e.g., nanofilled block copolymers.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Structural Multifunctional nanoMaterials

***Submitter*:** Gale A. Holmes

***Technological Innovation at Stake*:** Nanoparticles and nanodevices are being embedded in advanced engineering materials to accomplish multiple performance objectives in a single system. These nanotechnologies provide a mechanism for imparting additional functionality, e.g., energy dissipation, electrical property enhancement, self-repair, sensing, firehardening, or ballistic/blast protection, beyond a material's primary structural function. For example, the use of polymer matrix composites (PMCs) in aerospace applications has become a major driver for increasing fuel efficiency. However, unlike metals, PMCs are non-conducting and therefore do not have lightning strike capability. The integration of carbon nanotubes in these composite materials is being explored.

***Economic Significance of Innovation*:** Multifunctional nanoMaterials (MFnMs) have the potential to provide breakthroughs to strengthen current industries, e.g., aerospace, automotive, electronic and biological, and facilitate the emergence of entirely new industrial sectors. For example, manufacturers of the super-efficient Dreamliner proposed by Boeing and the F-15 fighter jet are seeking to increase operating efficiency and maneuverability while incorporating energy dissipation (lightning strike capability) into the non-conducting composite structure via carbon nanotubes.

***Technical Barrier to the Innovation*:** The key technical challenge confronting MFnMs is the integration of these new functions into the host material without sacrificing its structural integrity. In the case of introducing lightning strike capability in PMCs, this would involve incorporating the nanotube particles, which conduct electricity, without compromising the structural integrity of the PMC.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Advancement in this area is limited by the absence of metrologies linking key nanomaterial properties, host material properties and nanoscale interphases formed by their incorporation, to the key mechanical properties, including fracture toughness, stiffness and strain-to-failure, which control the structural integrity of the host material.

***Potential Solutions to Measurement Problem*:** Successes and failures in the current research literature of nanotechnology integration suggest that particle dimension, matrix particle adhesion, dispersion, stiffness, and intrinsic toughness of the host material are some of the key variables controlling the successful development of structural MFnMs. Therefore, metrologies linking nanomaterial properties to MFnM performance are essential for overcoming the current technical barriers.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue**:** Economical Full-Color Reprographics

Submitter**:** William E. Wallace

Technological Innovation at Stake: Color computer monitors are ubiquitous for desktop and laptop computers. Monochrome printers continue to dominate the printer market because color printers are significantly higher cost items. Printing of color graphics on demand is done by using reprographic toners that consist of dyes compounded with low-molecular-mass polyolefins (i.e., waxes). These waxed-based color toners are complex mixtures of organic materials that are extremely difficult to formulate and to characterize. The inability to measure the chemical properties, e.g., molecular mass, of this class of chemicals significantly increased the expense of color toners, thereby inhibiting their widespread use. Waxes, also called paraffins, as a class of chemical are not prominent only in toner manufacture, but impact other industrial processes and end user applications, e.g., formulation of lubricants, cosmetics, and food stuffs.

Economic Significance of Innovation**:** The color toner market was a $3 billion market in 2005, while the black toner market was a $17 billion market. Color toner was 6% of toner sales in 2000 but had only increased its market share to 15% by 2005. Adoption of color printing has been a slow process, primarily because of the high cost of manufacturing color toners. Color printing can potentially improve U.S. productivity; for example, color copies and printouts can convey complex technical and business information in charts, graphs, and presentations with much greater clarity and in a shorter time.

Technical Barrier to the Innovation**:** The single-chain characteristics of the waxes strongly impact their miscibility with the organic dyes; however, compositional analysis of the waxes is very difficult. As a result, synthetic processes must be held to tight tolerances because the poor quality of the analysis of the resulting material cannot be used with confidence to troubleshoot the synthetic process. This in turn means that process variables cannot be optimized to make the best product as cheaply as possible, quality control for manufacturing must be very high.

Stage of Innovation Where Barrier Appears**:** R&D and Production

Measurement-Problem Part of Technical Barrier**:** Chemical analysis methods of waxes give conflicting values for such single-chain properties as average molecular mass, molecular mass distribution, end group composition, and level of molecular branching. New analytical measurements and methods are needed.

Potential Solutions to Measurement Problem**:** 1) Continue on the current trial-and-error path of development and production; 2) Develop standard materials and methods to better understand each analytical technique and its random and systematic uncertainties; 3) Invent totally new methods, or methods that have never been applied to this problem before, to try to break the conflict between existing methods; 4) Use carriers that are not waxed based.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Wireless Functionality through MEMS

***Submitter*:** David Read

***Technological Innovation at Stake*:** Achievement of performance/price leadership in cost-competitive wireless products through the use of MEMS (micro electro mechanical systems) design features and components, for example, MEMS switches for RF signals. Adequate electrical performance, particularly fast and complete on-off switching and low power consumption, can be achieved with MEMS technology. RF switches are used in telecommunications, LANS, and other RF devices for civilian, medical, and military applications.

***Economic Significance of Innovation*:** Use of MEMS offers significant technical advantages in performance vs price in compact wireless devices. An example of an RF MEMS component is a switch, which opens and closes to an RF signal in response to a control voltage. Such switches are very economical compared to alternative designs. The market for RF MEMS in 2009 has been estimated at $1.1 billion, according to Jérémie Bouchaud and Dr. Henning Wicht of Wicht Technology Consulting, as reported in Microwave Engineering and elsewhere. This lags an earlier forecast from the same source, which had predicted a market of $1 billion 2007. This Measurement Need addresses one of the key causes of this lag, which remains an issue for future market acceptance of RF MEMS.

***Technical Barrier to the Innovation*:** Reliability, meaning the achievement of specified electrical performance over a predictable product lifetime, is an unsolved issue for RF MEMS devices. The field reliability of such MEMS components is untested, and no established methods for assuring the field reliability of such products, MEMS with moving parts, are known. Devices of suspect reliability cannot be marketed profitably; reliability complaints that arise after a product is introduced can be costly. This issue threatens the viability of a significant family of products.

***Stage of Innovation Where Barrier Appears*:** Production, specifically, quality control of product reliability; this type of quality control is a key part of the production process.

***Measurement-Problem Part of Technical Barrier*:** The main reliability issues are believed to involve changes in surface chemistry and surface electrical charge and unexpected evolution of the microstructure of the metal region that is flexed millions of times. These quantities must be measured in the laboratory, and controlled, by direct measurement or some more efficient strategy, on the production line.

***Potential Solutions to Measurement Problem*:** The solution has multiple parts: developing a practical understanding of the relationships between measurable material properties such as surface chemistry, surface charge density, and microstructure at the time of manufacture and in-service reliability of MEMS; development and fielding of advanced inspection tools for use in the production lines; and creation of a set of software to generate pass vs fail vs test further decisions based on inputs of quantitative material properties and quantitative inspection results.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Embedded Device Electronic Packaging Technology

***Submitter*:** David McGregor, Dupont

***Technological Innovation at Stake*:** High speed, miniature organic flexible and printed electronics with integrated passive and active components Embedded passive components allow for higher frequency (faster) operation and miniaturization of electronics, while increasing the active functions at lower power consumption and reduced radiated emission. Such attributes are essential for rapidly evolving consumer, industrial, automotive and medical electronics.

***Economic Significance of Innovation*:** Current technology uses Surface Mount Devices that hinder miniaturization and limit speed to below 1 GHz due to parasitic inductive delays, electromagnetic interference noise and high power consumption. The iNEMI 2006 roadmap forecasts, "Embedded Device Technology will result in profit of many millions of dollars from the added functionality and improved performance required by the commercial and military electronic sector."

***Technical Barrier to the Innovation*:** The industry needs thin dielectric materials, thinner than 500 nm, with dielectric constant of more than 2000 at frequencies above 10 GHz and measurement methodology for characterization at frequencies above 10 GHz. Current technology utilizes materials that are 25 microns thick or greater with dielectric constant of 20 or less. The industry needs embedded thin film and polymer thick film resistor materials at frequencies above 10 GHz and measurement methodology for characterization at frequencies above 10 GHz. Current technology uses thin film resistors but without measurement methodology. Use of polymer thick film resistors will reduce cost.

***Stage of Innovation Where Barrier Appears*:** R& D, Production

***Measurement-Problem Part of Technical Barrier*:** Improved high frequency performance requires new nanostructured-materials and fundamental models for understanding the structure-property relations. Small dielectric thickness induces nonlinear electromagnetic effects and time dependent dielectric breakdown that affects functional performance and reliability. Currently, the industry utilizes thick materials and measurements at DC or low frequencies, which are inadequate to advance this technology.

***Potential Solutions to Measurement Problem*:** The following would need to be addressed: (1)Mixing rule models for organic–inorganic hybrid materials engineered at nano-scale dimensions; (2) Impedance models and mixing rules for materials properties at high frequencies, which are extended above the relaxation frequency; (3) Measurement technique for nonlinear dielectric and conducting effects at functional voltages; and (4) Reliability models and acceleration factors for time dependent dielectric breakdown. Approaches include the development of non-destructive measurement techniques addressing the relevant materials structure and the corresponding functional property relationship. The techniques should offer nanoscale spatial resolution and the ability to distinguish physically similar domains at the molecular level. Available techniques for materials structure include soft x-ray synchrotron spectroscopy, neutron and x-ray relectometry, which can be combined with non-linear optical and dielectric spectroscopy. Standard test methods could be developed to inform researchers and product developers about specific problems within the materials or processing methods and serve as a common platform between parties.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Vacuum Ultra Violet Spectroscopy

***Submitter*:** Carlo Waldfried, Axcelis Technologies

***Technological Innovation at Stake*:** New vacuum ultraviolet sources and the corresponding spectroscopy. UV is being considered as a replacement for thermal curing processes and has the advantage of not using any of the thermal budget of a microelectronic chip. UV potentially enables new applications in semiconductor manufacturing process, such as UV cure of interconnect dielectrics, hydrogen removal and post processing of amorphous Silicon, or UV -annealing of gate dielectrics. New UV light sources, with spectral output at lower wavelengths than traditional UV lamps, emerge that have requirements for calibration sources at lower wavelength than currently available.

***Economic Significance of Innovation*:** The semiconductor industry is a significant driving force in the U.S. economy that arises from scaling down the feature size to the nanometer level, decreased power consumption and increased functionality speed. Novel UV processing can speed-up and eliminate several manufacturing steps. Wafer processing and associated metrology currently comprises 30–40% of the entire cost of semiconductor manufacturing. New UV light source spectroscopy may provide enabling technologies and revolutionary applications for the semiconductor manufacturing industry.

***Technical Barrier to the Innovation*:** At lower wavelength (<200nm), light sources are more susceptible to degradation over the lifespan of the source. The UV itself may be absorbed by atmospheric oxygen. Optical components require special attention to be compatible for the lower wavelength.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** There is a need for reliable sources of ultra violet radiation having wavelengths below 200 nm that can be used on-line. New calibration procedures for wavelength and intensity need to account for absorbing effects due to residual contamination, such as particles, residual oxygen and moisture. Currently used UV sources and detectors face significant challenges in achieving these requirements. This level of inspection is important because variations in features size one tenth of the nominal dimension often result in significantly different device properties. The development of new short wavelength UV sources and calibration procedures is critical in advancing manufacturing of designs and enabling new applications. What is needed is a stable, repeatable, well-characterized UV calibration source that can be utilized to calibrate the spectral output of industrially manufactured UV lamps. In addition, since the calibration measurement is sensitive to many different factors, a well-controlled measurement methodology and test setup needs to be established.

***Potential Solutions to Measurement Problem*:** New calibration sources, measurement techniques and measurement procedures are needed to accurately evaluate and develop light sources with vacuum ultra violet wavelength output. Explore photo-curable organic BCB, Teflon AF or inorganic hybrids and precursors that in comparison to SiO_2 have better and scalable dielectric properties.

Case Study – Measurement Needs

***Technology at Issue*:** Small Particle Monitoring For Advanced Semiconductor Manufacturing

***Submitter*:** Carlo Waldfried, Axcelis Technologies

***Technological Innovation at Stake*:** Control of particle concentration and size distribution is critical in advanced semiconductor manufacturing because it strongly affects yield and device performance. Cost-effective measurement of particle sizes below 90 nm is needed to improve device performance of current and future technologies.

***Economic Significance of Innovation*:** Cost-effective device development and manufacturing of integrated circuits with smaller feature size requires high resolution tools. The device performance and yield of advanced IC designs becomes more sensitive to smaller and fewer particles. Therefore it is necessary to control the particle contamination during the IC fabrication process. An innovative detection method is needed to capture smaller-sized particles.

***Technical Barrier to the Innovation*:** Reliable particle measurements for particle sizes below 90 nm will require new techniques based on shorter-wavelength radiation and with the stability and quality of synchrotron sources. Such sources and the corresponding detecting instrumentation of scattered radiation are not available for the manufacturing environment.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Current particle detection metrology is based on optical methods. Limitations are due to the relatively long wavelength of the optical lasers that are being employed, as well as detector designs and beam optics. Available particle measurement systems can accurately measure particle sizes down to 0.09 microns and work is being pursued in the industry to develop metrology capabilities to detect smaller particle sizes in response to the need of the semiconductor industry. While improved particle metrology capabilities do in principle exist, they are not readily available due to high cost.

***Potential Solutions to Measurement Problem*:** New laser sources and scattering techniques are needed to accurately and reliably measure particles 90 nm and below with cost effective metrology equipment that is capable of operation in the semiconductor manufacturing industry environment. Development and validation of new measurement techniques including those at synchrotron and neutron facilities. Development of standard methods and data for new instrumentation.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Materials Informatics: An Enabler for Innovative Materials Development

***Submitter*:** R. Munro

***Technological Innovation at Stake*:** To promote and accelerate technological innovations and to enable more efficient avenues to competitiveness, materials information resources must be transformed from isolated, unrelated activities to an integrated technology implemented across multiple computer platforms via the World Wide Web. Materials life cycles (discovery/development, characterization, implementation, and recovery) now involve multiple aspects of information processing (collection/capture, assessment/evaluation, mining, maintenance, and dissemination) known collectively as materials informatics (MI).

***Economic Significance of Innovation*:** Competitiveness and innovation are strongly dependent on timely access to reliable data and computational models. MI is an enabling technology that can control the rate of development and implementation in any materials sector. The impact, therefore, is not strictly a matter of the productivity that it enhances, but rather the control or dominance of whole market sectors.

***Technical Barrier to the Innovation*:** Traditionally, distinct aspects of MI have been addressed separately, resulting in many severe issues. The ultimate barrier may be considered the dynamic integration of materials selection, property data access (with specified temperature and stress conditions and level of reliability), and computational models (with real time, adaptable boundary conditions) into an iterative, product model optimization cycle. Other barriers relate to the interoperability of diverse data resources, the compatibility of data and computational resources, the ability to interrogate databases via automated remote access, and the suitability of linked resources for discovery of trends and relationships.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Underlying the full scope of technical barriers are three critical issues: interoperability (allowing two or more resources to be linked seamlessly), property specific data communications, and data quality. No adequate information standard addressing these issues in a unified manner exits today.

***Potential Solutions to Measurement Problem*:** The three critical issues need to be addressed through both technical and consensus standards. Technical standards require the development of functioning prototype systems. Consensus standards require worldwide participation and agreement through international standards organizations (particularly, ASTM and ISO), steering committees and workshops, and de facto protocol specification organizations (e.g., the World Wide Web Consortium).

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Health Care/Nanotechnology - Cancer Diagnosis and Treatment

***Submitter*:** Vincent A. Hackley

Technological Innovation at Stake: Nanoparticle-based vectors for detection and treatment of cancer. Success would result in precise in situ imaging/localization of tumors, sensitive ex situ detection, and localized application of chemotherapy directly to tumor cells. Innovations will provide for early detection, improved efficacy of anti-cancer drugs, and decreased toxicity of treatments to non-targeted cells.

***Economic Significance of Innovation*:** From the 2005 ASTM Workshop "Characterization of Nanomaterials for Medical and Health Applications," the cancer mortality rate in 2002 was identical to that in 1950; the healthcare cost associated with cancer treatment was $189 billion in 2002. Due to the potential benefits of nanotechnology in cancer treatments, by 2005, 61 nanotech drugs or delivery systems had been developed and 91 devices or diagnostic tests based upon nanotech had been developed. According to the National Cancer Institute, "nanotechnology will change the very foundations of cancer diagnosis, treatment, and prevention."

***Technical Barrier to the Innovation*:** Lack of a standardized, analytical cascade for the physical (physico-chemical) characterization of nanomaterial vectors and lack of knowledge of critical material parameters that influence nanomaterial transport, toxicology and effectiveness in biological systems; undefined clinical pathways for approval of nanomaterial-based drugs. These materials must be evaluated for both efficacy and toxicity before going on to clinical studies and FDA approval. Improved understanding of nanomaterial interactions in biological systems will also impact how new NP platforms are developed, as well as impact future FDA guidance on these materials and their approval.

***Stage of Innovation Where Barrier Appears*:** R&D and Production

***Measurement-Problem Part of Technical Barrier*:** Measurement protocols must be developed and standardized for the physical characterization of different nanomaterial classes under physiologic conditions. Properties include hydrodynamic size and size distribution, morphology, aggregation, stability, surface charge, zeta potential, chemical composition and purity. Parameters that impact nanomaterial behavior in biological systems must be identified and systematically interrogated.

Potential Solutions to Measurement Problem: Improved methods for physical characterization of nanoparticles under relevant conditions and R&D to relate physical (material) characteristics to biological interactions (e.g., toxicity, reactivity, mobility) and pharmacokinetics. Relevant reference materials, protocols, and internationally recognized consensus standards for measurements.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Multi-layer Nanostructures for Electronic and Photonic Devices

***Submitter*:** Grady White, Ed Fuller, George Quinn, Lawrence Robins

***Technological Innovation at Stake*:** Systems composed of multiple layers of 1nm – 50 nm thick films with diverse compositions and lattice parameters achieve dielectric, carrier mobility, and recombination properties that are unachievable in bulk or monolithic material devices

***Economic Significance of Innovation*:** Nanoscale structures and material diversity will enable smaller, cheaper, faster, and more powerful electronic and photonic devices that will maintain U.S. competitiveness in critical global arena. The 2005 global semiconductor market was $227 billion. A 2004 NRC report stated, "The US semiconductor industry is, today, the largest value added industry in manufacturing" and in 2005, the U.S. market share for microelectronics was 46%.

***Technical Barrier to the Innovation*:** A major barrier to implementation of devices based on complex multi-material structures is obtaining predictable performance and guaranteeing short- and long-term reliability. Specifically, stresses/strains from mismatch between layers and other sources affect carrier lifetimes and mobilities in electronic devices, emission/absorption energies in photonic devices, and lifetime to failure in both device classes. The barrier can appear during R&D because designers cannot confirm that design models are predicting accurate strain levels, during Production when components begin to fail on the wafer level, or End Use because customers want reliability predictions that are not available.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** To assess local fluctuations in critical electronic and optical properties in sub-micrometer devices, strains need to be measured with spatial resolution of 10 nm -30 nm. Current techniques are limited to about 500 nm.

***Potential Solutions to Measurement Problem*:** Development of tools for optical spectroscopic measurements with nanometer scale resolution. Simultaneous development of models or calibration procedures to quantify the strain from the spectroscopic data.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Strained-layer Engineering for High Performance Electronic and Optoelectronic Devices

Submitter: Martin L. Green, Ward L. Johnson

Technological Innovation at Stake: The introduction of strained layers into electronic and optoelectronic devices is being pursued by industry as a means of optimizing performance parameters such as electron mobility and optical emission wavelength. Further, scaling (adherence to Moore's Law) in Si microelectronics is an expensive proposition; however, through the use of strained Si layers, with their well documented higher carrier (electron and hole) mobilities, performance improvements may be achievable without scaling. Ken Rim of IBM has stated, "strain engineering replaced geometric scaling as the primary performance driver starting with the 90-nm technology node". Performance driven strain engineering will push devices close to the brink of mechanical failure, and it is essential to be able to characterize the strain and its distribution.

Economic Significance of Innovation: The silicon microelectronics industry, is, at $750 billion, one of the largest sectors of the global (and US) economy. Continued innovations in Si microelectronics, especially those that improve device performance without scaling, are of immense importance. The establishment of new strain-mapping tools will promote U.S. industrial innovation and competitiveness by filling a void in measurement science and technology that is impeding the development of near-term and emerging electronic and optoelectronic devices.

Technical Barrier to the Innovation: Strained silicon technology cannot be advanced independently of metrology improvements, as well as models for accurately predicting strain distributions. As stated in the International Technology Roadmap for Semiconductors 2005 (ITRS 2005), "although carrier mobility is already being improved by process-based stress, the inadequacy of stress metrology has become a greater issue." Efforts to proceed from simply manipulating strain, to true strain engineering, have been impeded by lack of characterization tools. Conventional X-ray and optical methods for determining strain attain resolutions of several hundred nanometers, inadequate for the sub-60 nm devices soon to be manufactured.

Stage of Innovation Where Barrier Appears: R&D

Measurement-Problem Part of Technical Barrier: There is no established approach for measuring the magnitude and distribution of strain with a resolution better than a few hundred nanometers. Techniques employing microbeam X-ray diffraction, and conventional micro-Raman spectroscopy, can achieve resolutions of only about 500 nm and 700 nm, respectively. To effectively map strain in device structures with sub-100-nm active regions, innovative measurement techniques must be developed with a resolution of ~15 nm.

Potential Solutions to Measurement Problem: Two potential approaches are identified here for nanoscale mapping of strain: 1) tip-enhanced Raman spectroscopy (TERS) and 2) electron-backscatter-diffraction (EBSD). TERS potentially will extend the spatial resolution of strain measurements to 15-20 nm. However, reproducible TERS results have not yet been achieved with respect to either spatial resolution or signal strength, and quantitative determination of strain has not been accomplished.

Case Study – Measurement Needs

***Technology at Issue*:** Thermoelectric Materials Metrology

***Submitter*:** W. Wong-Ng, N. Lowhorn, and M. Green

***Technological Innovation at Stake*:** Thermoelectric materials, i.e., materials that can directly convert thermal energy into electrical energy, and vice-versa, show great promise for vehicular waste heat recovery and solid-state refrigeration applications. The ability to recycle automotive waste heat (~75% of the energy content of each gallon of gasoline) into electricity to run a hybrid motor on the vehicle, or the vehicle electrical system, would greatly increase efficiency. Solid state refrigeration applications offer the possibility of "green" refrigeration, and also higher reliability due to no moving parts.

***Economic Significance of Innovation*:** The widespread use of thermoelectric materials for vehicular waste heat recovery could lead to a 10% reduction in fossil fuel usage. Further, as substitutes for conventional mechanical refrigeration, they would greatly reduce the amount of environmentally destructive refrigerants in use. The thermoelectric industry is potentially very large (perhaps $10B/year) and includes the automotive, electronics, aerospace, and military sectors.

***Technical Barrier to the Innovation*:** Thermoelectric materials suffer from low energy conversion efficiencies. Materials with conversion efficiencies 2 to 3 times greater than are presently attainable are needed for widespread commercialization of thermoelectric materials. However, this presents a difficult technical barrier because it involves minimizing thermal conductivity while maximizing electrical conductivity, two properties that are most often positively correlated.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** There are two aspects to the measurement problem. First, no acceptable metrology for reliably determining the figure of merit (the thermoelectric community calls this dimensionless quantity "ZT") of thin film materials exists due to the difficulty of separating the contributions from substrates. This is especially problematic since the highest conversion efficiencies reported thus far are for films. Second, a high throughput approach for synthesis and screening of thermoelectric thin films, which would accelerate materials optimization, is lacking.

***Potential Solutions to Measurement Problem*:** A scanning thermoelectric microscopy technique, based on scanning tunneling microscopy, would allow relatively fast property screening of combinatorial film libraries.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Advanced Force Measurements in Nanotechnology

***Submitter*:** Richard Gates & Robert Cook

***Technological Innovation at Stake*:** Nanoscale Measurement Accuracy: Atomic Force Microscopy (AFM) is widely used for characterizing surfaces at the nanoscale; however, accurate understanding of the forces being applied to surfaces is limited by the lack of SI traceable standards at the force scale applicable to AFM. This affects not only specific force measurements (adhesion, deformation, friction) but imaging as well since excessive forces can lead to structural deformations that alter the image and can lead to erroneous interpretation. Improved nanoscale measurement accuracy will enhance the ability to measure materials microstructures and properties at the nanoscale and increase our abilities to evaluate and enable MEMS structures.

***Economic Significance of Innovation*:** Ability to provide accurate nanoscale force measurements will enable better design of nanoscale devices (MEMS, NEMS) and lead to cost savings from improved tolerances. M/NEMs devices are involved in applications as diverse as safety (accelerometer sensors for automotive airbags), communication (optical switches), and entertainment (micromirror arrays for projection televisions) The worldwide MEMS market is currently approximately $30B/yr and forecast to grow very strongly in the foreseeable future.

***Technical Barrier to the Innovation*:** SI traceable calibrations are very difficult at the cantilever stiffness range typically observed in AFM (approximately from 100 pN/nm to 10 nN/nm). A single accurate determination requires specialized research equipment (e.g NIST electrostatic force balance – a unique, sensitive instrument capable of measuring nanonewton forces in an SI-traceable fashion) and laboratory facilities (NIST AML) and can take hours or days per determination.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** No readily available SI traceable, accurate, reference calibration cantilever standard is available.

***Potential Solutions to Measurement Problem*:** The solution is to develop reliable standards for the calibration of AFM force measurements. Large batches of very uniform reference cantilevers will need to be made with stiffness values relevant to AFM cantilever spring constants. The cantilevers must be calibrated with measurements traceable to the SI, and a standardized measurement procedure will be essential to enable both precise and accurate calibrations.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Nanotechnology Catalysts for Chemical and Materials Manufacturing

***Submitter*:** Daniel A. Fischer

***Technological Innovation at Stake*: :** Nanotechnology catalysts have the potential to revolutionize chemical and materials manufacturing by lowering costs in an environmentally friendly way by utilizing less expensive materials with designed functionality and efficiency. Nanotechnology catalysts could provide increased selectivity and activity over current catalysts by controlling pore size and particle characteristics.

***Economic Significance of Innovation*:** Catalysts are ubiquitous in the U.S. chemical industry, and they are both the cornerstone and the Achilles' heel for innovation. Current use of precious metal catalysts could be reduced or replaced by nanotechnology catalysts tailored at the nanoscale. In the chemical industry this would reduce feedstock and energy usage through improved catalyst selectivity. In petroleum refining, reducing alkylation temperature by improved catalysts would increase gasoline yield and lower precious metal usage. Optimized nanotechnology catalysts are expected to save $4B/year and 400 trillion BTU/year of energy. For a market assessment of Nanotechnology catalysts see:

http://www.chemicalvision2020.org/pdfs/economic_effect.pdf

***Technical Barrier to the Innovation*:** A key technical barrier is the lack of meaningful correlations between nanotechnology catalyst performance and the in situ identification and optimization of catalytic reaction intermediates. This is a challenging problem because of the chemical sensitivity required to identify a reaction intermediate in an in situ manor at the near-surface of a catalyst. Optimizing the reaction intermediates is an important key for rational design of new high performance nanotechnology catalysts. Without these correlations, it will be difficult for companies to move nanotechnology catalysts from R&D prototypes to the chemical plant real world.

***Stage of Innovation Where Barrier Appears*:** R&D, Manufacturing

***Measurement-Problem Part of Technical Barrier*:** Observing, identifying, and quantifying catalytic reaction intermediates must be performed in a non-destructive in situ manor during the complete catalytic chemical reaction at the nanoscale. Available lab-based techniques lack sufficient surface sensitivity, chemical resolution (the components are often chemically similar and thus difficult to distinguish) and sensitivity. R&D is needed to elucidate chemical reaction mechanisms initiated or controlled at the catalyst surface, as well as nanoscale surface chemistry.

***Potential Solutions to Measurement Problem*:** Recent developments in synchrotron based soft x-ray absorption spectroscopy hold the near term promise of the needed nanoscale spatial resolution while operating in situ with the ability to distinguish chemically similar molecular reaction intermediates in a non-destructive manor during the course of the catalytic chemical reaction. This measurement solution will be achieved by developing and applying synchrotron based measurement technology e.g. spatially resolving electron and x-ray detectors capable of operating at elevated temperature and pressure (in situ).

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Science-Based Performance Metrics for Advanced Dental Prosthetic Materials

***Submitter*:** George D. Quinn, NIST and Clifton Carey, Paffenbarger Research Center, American Dental Association Foundation

***Technological Innovation at Stake*:** Advanced ceramics and polymers are increasingly being used for dental prostheses, i.e., crowns and bridges. Current market insertion approaches are primarily based on short-term trial and error studies with little or no analysis of the failure mechanisms. Consequently, there is insufficient time before marketing to ascertain which materials and installation procedures will be successful and which will fail prematurely. Quantitative materials performance metrics introduction and the installation methodologies required that optimize their use will improve end use performance and provide manufacturers with methods to more quickly identify new materials capable of meeting such requirements.

***Economic Significance of Innovation*:** The rapidly increasing number of people in the U.S. who are retaining their natural teeth into old age is resulting in more dental restorations. Failures of dental restorations lead to degraded oral and systemic health and greater health care costs. Additionally, quality of life issues resulting from failed dental restorations include degraded communications, compromised diet, and lowered self-esteem. With the current market for dental prosthetics estimated at $20 billion, the dental materials manufacturers have responded with the introduction of new dental restoration materials at an unprecedented rate.

***Technical Barrier to the Innovation*:** New materials are being developed and marketed at a rate faster than clinical studies on material longevity can be completed. Currently, no guidelines or standards exist by which producers and clinicians can assess critical material properties or material requirements, and little science or sound engineering is applied to their considerations. Test methods based on improved understanding of failure mechanisms do not currently exist that will provide reliable prediction of material performance.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** New performance metrics and protocols based on research findings are needed for qualitative and quantitative information for these materials classes. Current laboratory tests do not correlate well with clinical performance. Often, incorrect types of tests are performed, or inappropriate properties evaluated (e.g., “crunch the crown” or unsuitable contact fatigue studies). In other cases, the right types of tests are performed, but use faulty procedures (e.g., strength by bend bars of inappropriate sizes and shapes). Unfortunately, there is no agreed upon standard method related to these materials for the intended applications. The fundamental studies to identify the key factors in dental material failure as correlated to clinical experiences have just been started in the last three years at the ADA-NIST laboratories. Standardized evaluation methods based on this new science are anticipated.

***Potential Solutions to Measurement Problem*:** Failure analysis and fractographic techniques can be applied to study the fundamental causes of both premature and normal in vivo prosthetic failures. With failure mechanisms identified, valid judgments can be made as to the required material properties. Laboratory test methods then can be devised to mimic or simulate the loadings and fracture modes that occur in service, and a suitable predictive model system developed.

Case Study – Measurement Needs

***Technology at Issue*:** Advanced Functional Ceramics

***Submitter*:** Terrell Vanderah

***Technological Innovation at Stake*:** Functional ceramics serve as critical enabling elements in electronic applications (resonators, filters, isolators, circulators, substrates, integrated capacitors, transducers, actuators, sensors) and energy applications (fuel cells, catalysts, nuclear power). The technical feasibility of next-generation applications frequently depends on the availability of ceramics with enhanced or entirely new properties, while commercial feasibility depends on cost reduction. This combination creates pressure (in industrial, academic, and government materials research labs) to find ceramic materials with distinct properties and reduced production costs.

***Economic Significance of Innovation*:** Electronic ceramics comprise the largest sector (~2/3) of the U.S. market for advanced ceramics (~$11 B in 2005). However, the market value of the devices and systems enabled are orders of magnitude larger than that of the materials alone. For example, the commercial market for microwave ceramics in communications applications (filters, resonators, circulators, substrates) is approximately $400 M, but these ceramics are needed as enabling elements for a device market on the order of $4 B, which in turn enables a systems market on the order of $40 B. Similar amplifications of value exist for every functional ceramic which serves as a critical enabling element (e.g. ferroelectric ceramics which serve as transducers for medical imaging technologies and sonar detection systems).

***Technical Barrier to the Innovation*:** Every deliberate effort to discover new materials or to improve material processing begins with the knowledge of what works now, or almost works, particularly regarding chemical composition and the conditions under which the materials are stable. For many functional ceramics, including some already in commercial use, the paucity or complete lack of relevant, reliable data is an impediment to R&D, cost reduction, and successful development of innovative new materials.

***Stage of Innovation Where Barrier Appears*:** R&D, Production

***Measurement-Problem Part of Technical Barrier*:** Four significant barriers exist: 1) the material system of interest may not have been studied; 2) the system may have been studied, but the data are proprietary and not available to the general research community; 3) the system has only been partially studied and/or the data are unreliable; and 4) the data are not available in a readily accessible and usable database.

***Potential Solutions to Measurement Problem*:** Phase equilibrium data provide the essential physicochemical information pertaining to chemical composition and the conditions of temperature and pressure under which pure compounds (and mixtures thereof) are thermodynamically stable. R&D is needed to measure, gather, evaluate, and disseminate phase equilibrium data as an integrated effort. Examples include new ceramics needed for 1) practical solid oxide fuel cells and 2) migration to advanced broadband wireless applications using existing cellular infrastructure: in both cases, information exists in disparate, sparse reports that are either inadequate or unavailable to test engineers. The R&D efforts needed must be coordinated through roadmaps and federal funding, dedicated studies of identified high priority systems, systematic data evaluation, and development of a centralized, web-accessible data system exploiting new and evolving data communications languages such as XML and MatML.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Hydrogen economy: H_2 storage

***Submitter*:** Lawrence P. Cook

***Technological Innovation at Stake*:** Hydrogen (H_2) powered automobiles can lessen dependence on diminishing and unreliable oil supplies, and simultaneously contribute to reduction of atmospheric pollution and global warming (if the approach taken is to use nuclear power for production of hydrogen, thereby avoiding fossil fuels, and helping to contain global warming) . This technology can be realized safely only if suitable materials for on-board, solid state H_2 storage are developed.

***Economic Significance of Innovation*:** Hydrogen is being seriously considered by government and industry as an alternative to gasoline because it is a non-polluting fuel that also reduces reliance on foreign oil (automobiles consume more than $50B/year of petroleum-derived fuels). However, the wide-spread use of H_2 as a fuel source for fuel-cell based automobiles is greatly inhibited by the lack of infrastructure (production, delivery, and storage).

***Technical Barrier to the Innovation*:** A recent DOE report identified H_2 storage as the most critical problem to solve towards achieving the hydrogen economy. Current capabilities for on-board storage of compressed or liquefied H_2 are neither safe (high pressure containers) nor practical (insufficient energy density). Solid-state storage of H_2 by adsorption in low mass alloys, however, offers great promise, but the H_2 release and regeneration parameters in the best known storage materials are not yet acceptable.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Advancement is hindered by the lack of an optimized evaluation technology for H_2 storage materials. Measurement of a material's H_2 storage capacity involves both equilibrium and kinetic aspects of the adsorption/desorption process at the atomic level. Currently, enthalpy, mass change, and adsorption/desorption kinetics are measured on individual bulk materials, a time-consuming and relatively inefficient approach. A dramatically more rapid methodology is needed to achieve a viable, large-scale, systematic materials evaluation study.

***Potential Solutions to Measurement Problem*:** Since H_2 adsorption is a thermal process, it can be measured calorimetrically. Using MEMS nanocalorimeter arrays currently under development at NIST, it will be feasible to measure H_2 adsorption/desorption thermodynamics and kinetics combinatorially on thin-films, significantly reducing the materials preparation effort and increasing the efficiency of the screening process. The MEMS approach allows cost-effective fabrication of large numbers of miniaturized sensors with nano-scale sensitivity, which greatly increases the measurement rate and the number of data points that can be generated for a given set of materials.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Lead-Free Electronics

***Submitter*:** Igor Levin

***Technological Innovation at Stake*:** Current drivers for next-generation electronic applications include cost reduction, aggressive miniaturization, and increased functionality of devices. Further, European and Japanese markets demand lead-free electronics. These demands necessitate new lead-free ceramic materials (both amorphous and crystalline) capable of performing critical functions ranging from capacitors and filters to data storage media to transducers and actuators. The new materials are needed either as on-chip thin layer heterostructures or thick films for integration in microelectronic and ceramic multilayered architectures, respectively.

***Economic Significance of Innovation*:** Most advanced electronic devices incorporate electronic ceramics either as discrete components or as thin layers in integrated circuit devices. Examples of their applications include ultra-thin amorphous layers used in the memory devices, thin polycrystalline films of high-dielectric constant low-loss materials for capacitors and phase shifters in wireless devices, and bulk piezoelectric components used as transducers and actuators. Development of new electronic ceramics impacts the entire multi-billion electronic industry, including its computer, data storage, and wireless communications sectors. Additionally, the European Union passed the Restriction on Hazardous Substance (RoHS) directive in 2002 that is to go into effect in July 2006. Lead-free electronics are mandatory.

***Technical Barrier to the Innovation*:** At the forefront of R&D, materials developments and adaptations usually require an understanding of functional mechanisms and the underlying structure-properties relations that govern them, both of which frequently are lacking for advanced electronic materials.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The critical properties of advanced electronic ceramics (e.g. dielectric, ferroelectric, colossal magnetoresistance) increasingly appear to be strongly influenced by details of the local structure. Local structure measurements (e.g. atomic displacements and their correlations) are needed to assess the structure-property relations. Currently, these measurements are hindered by the need for specialized high-energy high-brightness probes and the lack of “plug-in” local structure models.

***Potential Solutions to Measurement Problem*:** Local structure details that deviate from strict long-range periodicity are manifest as a diffuse scattering and fine structure in diffraction patterns and absorption spectra. These features can be measured using highly specialized equipment with synchrotron x-ray facilities, pulsed neutron sources, or electron probes. Data from these studies can be used to develop local structure models tailored to industrially-relevant types of materials. Models describing common deviations from the average structure then could be incorporated into widely used data analyses codes to ensure their transfer to industrial users.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue**:** Autobody Sheet (Die Face) Engineering

Submitter**:** Lyle E. Levine

Technological Innovation at Stake**:** The automotive industry is increasingly turning to high strength steel and aluminum body sheet for vehicle weight reduction. Weight reduction is critical for increasing fuel economy.

Economic Significance of Innovation**:** The design of working die sets is the largest single fixed cost and the longest lead-time item in automobile production. This problem becomes much greater for high strength steels and aluminum alloys, greatly inhibiting the introduction of these new materials into automotive production. This technology can increase fuel efficiency while not sacrificing safety.

Technical Barrier to the Innovation**:** The high cost and long lead time of die face design comes from a basic inability to predict what the final component shape will be for a given die design. Existing models make critical assumptions that are known to be incorrect and industry is seeking new standard test methods that can provide more accurate material model parameters.

Stage of Innovation Where Barrier Appears**:** R&D

Measurement-Problem Part of Technical Barrier**:** The largest die face modeling errors occur when metal samples undergo alternating tension and compression during forming. Existing tension-compression tests were designed for testing metal sheets of significantly greater thickness than are now commonly used in automotive production and new mechanical test procedures are needed.

Potential Solutions to Measurement Problem**:** A new standard mechanical test method using a complete tension compression deformation cycle is required so that accurate material model parameters can be measured for these new materials.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Reliability Engineering of Microelectromechanical Systems (MEMS) Devices

***Submitter*:** Robert Cook

***Technological Innovation at Stake*:** The development and commercial introduction of MEMS-based devices for a broad range of applications is impeded by a lack of measurement techniques to determine, predict and verify device reliability (device performance over service life). The lack hampers materials and process selection and restrains MEMS devices to the few (rather simple) commercial products for which there are substantial empirical experiences (in restricted environments) of reliability. Without advanced measurement techniques to refine and demonstrate MEMS reliability, customer acceptance of MEMS devices will remain low and MEMS innovators, developers and manufacturers will have little economic incentive to commercialize products. Such products might include match-stick size bio-toxin sensors, artificial eyes and the robotic surgical tools to insert them, ubiquitous shock sensors and bright video screens for hand-held devices, or low-cost patches and implants for automated drug delivery.

***Economic Significance of Innovation*:** The current, worldwide MEMS device market is about $55 B, dominated ($25 B) by the air-bag trigger accelerometers and engine pressure sensors used in automobiles and the fluid pumps ($20 B) used in inkjet printers. Mirror arrays used in digital optical projectors make up a large part of the rest of the market. Market growth expectations are strong: ~300% in the next two years for accelerometers as shock sensors are introduced into hand-held devices; ~200% in five years for digital mirrors as arrays are introduced into large screen HDTVs; and, ~100% in five years for inkjet printer hardware as wide-formats and non-aqueous inks become pervasive.

***Technical Barrier to the Innovation*:** The small sizes, new applications and unfamiliar environments for many MEMS devices introduce unknown reliability detractors and thus an inability of MEMS manufacturers to refine designs, materials and processes to improve reliability. For example, it is widely thought that extrinsic particulate damage is the major limitation of MEMS lifetime, rather than intrinsic material degradation as in larger mechanical systems: Identifying this limitation and re-designing affected systems using unfamiliar design principles at ultra-small scales is obviously a challenge.

***Stage of Innovation Where Barrier Appears*:** Marketing, End Use

***Measurement-Problem Part of Technical Barrier*:** Reliability engineering follows the sequence of (i) identification of defects, (ii) measurement of defect kinetics, (iii) development of lifetime models and (iv) verification of lifetime predictions. Measurement tools are required in each of these areas, but are severely lacking in (ii)-(iv) for MEMS devices. In the case above nano-scale tools need to be developed to identify lifetime-limiting aspects of particulate damage, measure kinetics of damage evolution under controlled loading, develop physically-based models to predict damage evolution, and measure lifetimes of statistically representative numbers of devices to verify the consequent predictions.

***Potential Solutions to Measurement Problem*:** Manufacture realistic MEMS test structures (mechanical, thermal, electrical, chemical, fluidic) to enable measurement (in application environments) of material kinetic properties related to defect appearance. Develop non-empirical lifetime models, the associated analysis software, and capability to test many devices rapidly to enable lifetime prediction verification.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Alternative Energy/Photovoltaics

Submitter: A. Hunter Fanney

***Technological Innovation at Stake*:** Early-adapters in the building industry have begun using photovoltaics to meet a portion of their electrical energy needs. Significant market penetration of photovoltaics for building applications is anticipated to meet increasing international demand for energy and environmental concerns associated with non-renewable energy sources.

***Economic Significance of Innovation*:** Photovoltaic module production is accelerating due to increased demand for energy, decreasing costs, and financial incentives. The photovoltaic market is projected to quadruple to $20 billion by 2010. One of the greatest issues facing the industry is the uncertainty associated with photovoltaic module power ratings. The economic consequence of this uncertainty will approach $200 million by 2010. Under rated power ratings result in a significant loss of revenue to the manufacturer. Over rated panels fail to meet customer expectations or those of local/state/federal agencies that provide financial incentives.

***Technical Barrier to the Innovation*:** As a result of large power rating uncertainties, end users are not confident that the photovoltaic modules they purchase will produce the manufacturer's stated electrical power. Significant uncertainties in stated power ratings make it difficult for end-users to compare competitive photovoltaic products and make informed economic decisions. Industry's use of various lamp sources to replicate the solar spectrum, the lack of spectral measurements coincident with power measurements, and lack of standard testing methodologies are leading contributors to the uncertainty.

***Stage of Innovation Where Barrier Appears*:** Marketplace

***Measurement-Problem Part of Technical Barrier*:** Accurate measurement techniques to capture the spectrum of high-speed (<10 ms) flash solar simulators used in industrial environments do not exist. Improved measurement techniques resulting in reduced uncertainties in spectral and temperature response functions for photovoltaic cell technologies need to be developed. Methods to accurately measure the temperature of photovoltaic modules during high-speed flash testing need to be developed.

***Potential Solutions to Measurement Problem*:** R&D to develop lamps that closely replicate the solar spectrum. Improved high-speed spectral measurements that can be realized in an industrial environment. An in-depth uncertainty analysis to identify individual measurement contributions to overall uncertainty budget. The combined results of these efforts will reduce the overall uncertainty in photovoltaic module ratings.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** Wireless Sensor Networks

***Submitter*:** William Healy

***Technological Innovation at Stake*:** Wireless sensor networks promise to allow for pervasive monitoring of buildings, machinery, and environmental conditions. The greater availability of real-time information afforded by wireless sensor networks can improve the performance of various engineered systems and provide information to ensure the safety of people and infrastructure.

***Economic Significance of Innovation*:** The use of wireless sensor networks will lead to more efficient operation of equipment by providing data that can be used to either improve control or to better predict the health of that equipment. While such data could be obtained from wired networks, the cost and complexity of installing wires in a building or structure can often be prohibitive. Estimates of wiring costs range from $0.67 per foot for new construction to upwards of $2000 per foot for existing high-security facilities (e.g. nuclear reactors). Sales of wireless sensor network units are projected to climb from 2 million in 2004 to approximately 168 million units by 2010, creating a market of $5.9 billion. While the potential market suggests significant impact, resulting savings in costs and energy of processes that take advantage of sensor networks are even more compelling. A few examples…a) A study has claimed that the use of sensor networks to monitor buildings and HVAC equipment in California could save the state $7 billion in energy costs. b) The Federal Highway Administration has indicated that 30% of bridges in the United States are structurally deficient, so the use of wireless sensor networks to monitor the health of these structures could help focus costly rehabilitation efforts on those structures that are most susceptible. c) Department of Energy research suggests that wireless monitoring of industrial motors could lead to energy savings of 11-18 %, resulting in electricity savings amounting to $1.3 billion by 2025.

***Technical Barrier to the Innovation*:** Potential end-users of wireless sensor networks have shown reluctance towards using them in a wider range of applications because of uncertainty in the reliability of the wireless links. Propagation of various wireless transmissions over a range of building types is not well understood, and users do not have a way of ensuring that wireless networks will deliver data reliably.

***Stage of Innovation Where Barrier Appears*:** End Use

***Measurement-Problem Part of Technical Barrier*:** Methods for measuring the reliability of wireless links in actual use are currently in their infancy. While signal strengths can be measured, detection of intermittent interference from other sources evades many measurement systems.

***Potential Solutions to Measurement Problem*:** Three potential solutions to the measurement problem have been identified. First, the formation of a standard definition of reliability would allow end users to compare products in an equitable fashion. Second, on-board capabilities to measure signal strength and interference sources could be developed to gauge the reliability of data transfer. Third, standard evaluation methods to measure the reliability of data transfer in and around buildings could be developed.

***Technology at Issue*:** Gaseous Air Cleaners

***Submitter*:** Cynthia Reed and Andrew Persily

***Technological Innovation at Stake*:** Gaseous air cleaners that can remove the wide range of contaminants present in typical building environments. To date, gaseous air cleaners have been used primarily in industrial applications to remove a small number of known contaminants that interfere with manufacturing processes. They have not been widely implemented in other building types because the range of contaminants is generally not well known. In addition, the lack of clear target concentrations and the existence of interfering gases have led to the development of new air cleaning strategies which have not been well-studied for cleaning performance.

***Economic Significance of Innovation*:** Using gaseous air cleaners in non-industrial buildings has the potential to save the U.S. from 10 to 20 billion dollars by reducing sick building syndrome symptoms and 12 billion dollars through improvements in worker productivity. Air cleaning can also allow reductions in the amount of outdoor air brought into buildings, which is associated with energy consumption for heating and cooling on the order of $7 billion in U.S. commercial and institutional buildings. The residential air cleaner market (estimated to be about $500 million and increasing) includes several technologies that have not been evaluated due to the lack of test methods, and consumers may be buying air cleaners that are ineffective or even harmful to human health.

***Technical Barrier to the Innovation*:** Given the lack of a rating method, potential users do not have enough information to distinguish between the capabilities and capacities of different technologies. The inability to determine the capacity or lifespan of an air cleaner also makes it difficult to develop reliable replacement schedules. The lack of rating methods has resulted in a market barrier due to the inability to compare the performance of different products... The lack of such methods is primarily a function of the need to characterize performance for a range of contaminants with no clear target concentrations and the presence of interfering gases.

***Stage of Innovation Where Barrier Appears*:** Marketplace

***Measurement-Problem Part of Technical Barrier*:** While it is relatively straightforward to measure effectiveness given a single or small number of known contaminants at high concentrations, it is far more challenging to assess performance to a mixture of many contaminants at relatively low concentrations and in the presence of interfering gases. In addition, air cleaner removal currently is measured in laboratory tests, and there is no way to reliably relate these results to installed performance in a building. There is also a need to measure product life or capacity, particularly the remaining capacity in an installed system.

***Potential Solutions to Measurement Problem*:** Laboratory chamber and field performance tests as well as fundamental mass transport modeling to determine the relationship between gaseous air cleaner effectiveness measured in the laboratory to the installed effectiveness in actual buildings. Development of accelerated performance tests to predict useful lifetime of air cleaners. Development of a gaseous air cleaner rating system (similar to the MERV system for particle filters) based on a standard test method.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Nano-Additives for Fire Resistant Plastics and Composites

***Submitter*:** Marc Nyden and Jeffrey Gilman

***Technological Innovation at Stake*:** Thermoplastics and composites made from hydrocarbon polymers can improve the affordability, strength-to-weight ratio, and durability of manufactured products. Unfortunately, the use of these materials in buildings and vehicles is limited because of their inherent flammability and poor thermal stability. Nanoadditives, including clays, layered double hydroxides, and nanotubes have been shown to reduce costs, increase thermal stability, reduce flammability, and enhance mechanical properties when they are homogeneously dispersed in polymers.

***Economic Significance of Innovation*:** One third of the $300 B world wide annual market for polymer based products is required to meet a regulatory flammability requirement. To the extent that we can develop reliable methods for their preparation, characterization, and evaluation, products made from polymer nanocomposites will be more resistant to heat and fire, and, at the same time, lighter, stronger, and less expensive than anything made from the present generation of materials, opening the way for U.S. industry to introduce new products in the construction and transportation sectors.

***Technical Barrier to the Innovation*:** The flammability of polymer nanocomposites depends critically on how the nanoadditives are introduced into the polymer matrix. However, there are no quantitative metrics for assessing the degree of nano-scale mixing/dispersion/ interaction attained in the composite and how this affects the properties of interest. In the absence of this knowledge, it is impossible to determine the nature and amount of nanoadditive needed to obtain optimal performance.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The absence of any quantitative metrics makes it difficult to establish a reliable relationship between properties of interest and the degree of dispersion assessed by methods such as microscopic images and scattering measurements. New methods are needed for making 3-D measurements of the dispersion of nanoadditives in polymer matrices, for quantifying the extent and quality of mixing, and for interpreting how these characteristics affect the key properties of the bulk material.

***Potential Solutions to Measurement Problem*:** A program of study is needed that involves statistical analysis of experimental data to develop standards for assessing the degree of mixing and molecular modeling, to reveal the relationships between the structures and properties of these materials. This is a challenging task because of the enormous range of time and length scales involved in the processes by which nanoscale interactions propagate to produce the macroscopic properties of interest.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Low Flammability Beds

***Submitter*:** Richard G. Gann

***Technological Innovation at Stake*:** The mattress industry has developed products that will significantly reduce the life and property loss from fires in homes. A key innovation in these mattress designs is wrapping the mattress and box spring in a thermal barrier fabric that limits the burning of the (interior) combustible materials.

***Economic Significance of Innovation*:** The U.S. mattress industry sells over 40 million units per year, with total sales of about $10 B. Each year, about 14,000 bed fires cost the United States 300 lives, 2,000 serious injuries, and $300 M in direct fire loses. Most of the fatalities and losses result from fires that have proceeded to room flashover. The new mattresses have been demonstrated to reduce burning rates sufficient to make flashover far less likely. A new Federal regulation sets a maximum allowable burning rate for the mattress set, using a test method developed at NIST. This is expected to lead to a major reduction in losses from and the costs of bedroom fires. The lack of a standard measurement method for the thermal barrier fabrics stifles the development of new or improved fire barrier materials. It also affects quality assurance of the final product, exposing both the fabric and mattress manufacturers to product liability claims.

***Technical Barrier to the Innovation*:** The reliability of the new products in meeting the burning rate criterion depends on the assured functionality of the thermal barrier layer. At present, a test methodology to quantify the insulating performance of this layer fails to exist and each of the larger mattress manufacturers is using its own unique protocol. Each batch of material from a fabric manufacturer must thus pass multiple tests if the company wishes to sell to a broad market. The small and midsize mattress manufacturing companies have no protocols.

***Stage of Innovation Where Barrier Appears*:** R&D and Marketplace

***Measurement-Problem Part of Technical Barrier*:** There is no standard test for measuring the thermal protection afforded by a barrier fabric in a manner that accurately simulates actual fires.

***Potential Solutions to Measurement Problem*:** Suitable measurement method(s) that define and capture these properties need to be developed and standardized. An accurate measure of the performance of the thermal barrier materials includes identification of the material properties that resist the passage of flames, the properties of the ignition source(s), and needed values of these properties under incipient fire conditions.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Advanced Concrete Materials

***Submitter*:** Edward J. Garboczi

***Technological Innovation at Stake*:** A significant market barrier to innovative concrete and cement products is the lack of suitable test methods and methodologies to measure their long-term performance. Concrete is the chief US infrastructure material and must have adequate long-term (e.g., decades) performance. The use of durable concrete products could potentially reduce the life-cycle costs of the U.S. concrete infrastructure by 50 %. Innovative concrete and cement products are being developed with the goal of significantly enhanced long-term performance.

Economic Significance of Innovation: According to the American Society of Civil Engineers, the cost associated with repairing the US infrastructure is currently projected to be $10T over the next 20 years. The use of more durable concrete products would significantly extend the life of the concrete portions of the U.S. infrastructure that will be built (e.g., bridges, pipes, pavements, foundations, office buildings, residential houses) thus saving substantial sums of money over the life of the infrastructure construction.

Technical Barrier to the Innovation: The specific physical, chemical, and mechanical mechanisms that contribute to long-term durability within concrete products have not been identified. Procedures currently in use for assessing long-term concrete durability in consensus standards are empirically based and unreliable or based on long-term (multi-year) performance measurements. This results in an extremely slow rate of technological innovation within the concrete industry.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Current durability tests purport to accelerate the rate of degradation under various scenarios. This acceleration is totally empirical – the correct degradation mechanisms are not known, no one knows which mechanism is being accelerated, and no one knows how to relate accelerated test time to real time. The chemical and physical kinetics of the measurements are non-existent. Appropriate performance-based tests must be developed, incorporating known degradation mechanisms, which will lead to material selection based on long-term performance metrics.

***Potential Solutions to Measurement Problem*:** R&D needs to be conducted to identify the mechanisms related to the long-term durability of concrete. Working with consensus standards organizations, test methods and long-term performance rating methodologies need to be developed that utilize the identified mechanisms and associated measurements to predict concrete durability in the environment of interest.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Residential Fuel Cells

***Submitter*:** Mark Davis

***Technological Innovation at Stake*:** The fuel cell industry is in the process of developing residential fuel cell units that will utilize natural gas or hydrogen as the fuel source. A key innovation in many of the units is the ability to meet not only the electrical needs of a residence, but the space and water heating loads as well.

***Economic Significance of Innovation*:** The widespread adoption of residential fuel cell systems will reduce the nation's dependence on foreign sources of energy by offering efficiencies that can approach twice that of central power plants, eliminating transmission losses associated with the electrical grid, and reducing environmental emissions. The number of residential-scale stationary fuel cell systems being produced doubled in 2002 and 2003, although most of those systems were for technology demonstration. As fuel cell systems become commercially viable, residential-scale stationary fuel cells are expected to be a large segment of the market, and the $40 million stationary fuel cell market in 2004 is predicted to grow to $10 billion by 2010.

***Technical Barrier to the Innovation*:** As residential fuel cells approach marketability, potential consumers do not have the necessary metrics to judge the economic impact of units offered by various manufacturers for their particular application. The economic feasibility of a stationary fuel cell system depends greatly on the climate, electric and thermal loads, energy prices, and the manner in which the unit is operated. To date, no effort has been made to quantify the real-world performance of residential fuel cell systems. A clear picture of the economic benefits of residential fuel cells would accelerate the widespread adoption of the technology.

***Stage of Innovation Where Barrier Appears*:** Marketplace

***Measurement-Problem Part of Technical Barrier*:** The development of a rating methodology to predict the real-world performance of residential fuel cells would require detailed performance measurements of residential fuel cell systems in a variety of sizes, types, and operational strategies. Test methods would then need to be developed that effectively communicate the performance of such systems while minimizing the test burden for manufacturers. Further performance testing would also be required to validate the test methods and rating methodology.

***Potential Solutions to Measurement Problem*:** A standard method of test to determine residential fuel cell performance at various environmental, electrical, and thermal loads. Development of a rating methodology that predicts "real world" performance from a limited number of laboratory tests. Deployment of systems in real-world applications with intensive instrumentation for validating rating methodologies.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Fire Resistive Materials (FRMs) for Buildings

***Submitter*:** Dale P. Bentz and Christopher White

***Technological Innovation at Stake*:** Fire resistive materials (FRMs) are critical to the development and protection of constructed facilities, especially high rise steel structures. To date, spray-applied mineral fiber and gypsum-based materials have been employed by the construction industry. Next generation materials such as foamed concrete and intumescent coatings have limited access to the marketplace, as their performance can not be differentiated from that of existing materials. Even with their critical role in environmental security, there is no materials science-based fundamental understanding of performance. The industry relies on historical performance of existing materials, which results in a frozen marketplace with little or no innovation. Without fundamental material-science-based characterization, performance prediction using advanced structural and fire dynamic models is significantly impeded. The durability of these critical materials can not be addressed until the underlying performance metrics are developed and standardized.

***Economic Significance of Innovation*:** In the U.S., FRMs are the principle passive fire protection means allowing for occupancy of all tall buildings. Next generation materials can greatly increase passive fire protection allowing critical time for evacuation and greater protection of physical infrastructure. Development of a robust material-science-based measurement infrastructure for FRMs will increase the competitiveness of U.S. manufacturers in the global market (estimated at $200 M).

***Technical Barrier to the Innovation*:** Manufacturers are focused on product performance in a threshold fire test (ASTM E119-type fire testing conducted at Underwriters Laboratory (UL) or other comparable laboratories). The manufacturers consistently lack the in-house measurement tools and methods to reliably predict in advance whether their materials will pass this test. Products are marketed based on the hourly ratings that they achieve in this test and not true materials science-based measures of performance.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Measurement techniques are needed to quantitatively characterize the three-dimensional microstructure of these materials so that links between microstructure and performance can be identified and exploited. Measurement methods are also needed to quantify the thermal conductivity and adhesion properties of these materials, specifically at high temperatures.

***Potential Solutions to Measurement Problem*:** Three-dimensional microstructures can be quantified using x-ray microtomography. New measurement techniques can be developed (and are being developed) and standardized for determining the necessary thermophysical and adhesion/mechanical properties of FRMs.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Advanced Fire-Resistant Structures

***Submitter*:** Anthony Hamins

***Technological Innovation at Stake*:** The construction industry is predisposed to use innovative materials, designs, and building practices to reduce the costs associated with fire safety. The introduction of these innovations to the building community is currently limited by the lack of validated engineering-based computational tools to predict fire growth and the performance of structural elements and assemblies under fire load.

***Economic Significance of Innovation*:** The construction industry forms a large fraction of the US economy, valued at greater than $1 T annually. A significant fraction of construction costs involves implementation of fire safety features. As most fire safety requirements currently are prescriptive, rather than performance-based, construction costs are inflated by more than one-half percent, or about $5 B annually. Without the necessary tools to develop and quantify the cost of possible design options, architects and engineers are constrained from realizing effective solutions.

***Technical Barrier to the Innovation*:** The lack of standard methods of test, methodologies to interpret test results, and facilities needed to validate predictions form a substantial barrier to the development and introduction of innovative materials, designs, and building designs. The degree of complexity of the interacting disciplines of fire dynamics, heat transfer, and structural dynamics preclude the use of existing test procedures that address only one of these disciplines. The current lack of appropriate test methods, methodologies, and structural fire testing facilities precludes the ability to demonstrate that proposed innovations are technically feasible, safe, and economically viable.

***Stage of Innovation Where Barrier Appears*:** Research and Development

***Measurement-Problem Part of Technical Barrier*:** Accurate thermo-mechanical measurements of the fire test environment and structural response of elements or assemblies are needed for model validation. Accurate measurements pose technical challenges associated with control of the thermal and mechanical boundary conditions, and quantification of the resulting stresses, strains and heat fluxes under severe and complex measurement environments characterized by high temperatures (above 1000 ^{o}C), large forces (exceeding 5 MN), and bulky specimen sizes (greater than 10 m). Methodologies are needed to account for accumulated uncertainties in the estimate of safety margins for structural performance.

***Potential Solutions to Measurement Problem*:** R&D to develop validated computational tools, standard methods of test, and methodologies to accurately interpret test data for the prediction of fire growth and the performance of structural elements and assemblies under fire load.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Fire-safe Building Products

***Submitter*:** Richard G. Gann

***Technological Innovation at Stake*:** New technologies for less hazardous building products are under development in industrial and government laboratories. Conventional materials used for these products burn readily and generate fire environments whose toxicity results in one of the worst fire death rates in the industrialized world.

***Economic Significance of Innovation*:** The direct losses from fires in the United States exceed $10 B annually. The total cost of fires is approaching 20 times that. Fire deaths and serious injuries top 20,000 per year. Most of the fatalities and property losses result from fires that have proceeded from room flashover from home furnishings and interior finish. Modified or alternative polymers and new fire retardant treatments reduce the burning rates of these products and thus the threat to life and property. Beneficiaries of these advanced products range from the dwelling owner and occupants to the insurance companies.

***Technical Barrier to the Innovation*:** For most building products, there is a prescribed performance level on an ignition or flame spread test. There is no code requirement that limits the toxic potency of the smoke generated during burning. As a result of these, there is no incentive for manufacturers to make products that perform better, i.e., burn less vigorously and produce less toxic smoke).

***Stage of Innovation Where Barrier Appears*:** R&D, marketing

***Measurement-Problem Part of Technical Barrier*:** The barriers are founded in the lack of a means for both appraising (on a continuous, rather than a pass/fail basis) the fire performance of a product in its in-use environment and coupling the requisite measurement methods. With such a construct in place, it would become possible to incorporate current fire property measurement methods or devise new, more appropriate ones.

***Potential Solutions to Measurement Problem*:** For flame spread standards, the solution lies in linking the existing measurement methods to the fire performance of real products and institutionalizing the ensemble into standards. For smoke toxicity, the output of each candidate measurement methods needs to be validated against fire performance in room fires.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Fire Suppression Systems

***Submitter*:** William Grosshandler

***Technological Innovation at Stake*:** Introduction into the marketplace is at stake for a variety of innovative fire suppression systems (water sprays, specialized sprinklers, fogs, powders, dual-acting, gas mixtures, solid propellant) that may offer significant savings in installation and operation costs, or fire protection.

***Economic Significance of Innovation*:** Automatic fire suppression systems are required in virtually all new commercial construction and transportation systems, with estimated annual sales of $2 B. Flexibility in the type of suppression system that could be made available to the designer/owner would allow for market forces to drive the costs down and encourage the adoption of fixed fire suppression systems in more communities. The biggest impact would be in the residential retrofit market, where automatic suppression systems could lead to more than $1 B/yr reduction in property loss and a thousand lives saved.

***Technical Barrier to the Innovation*:** Performance-based measurement standards do not exist that demonstrate the benefit of competing, innovative automatic fire suppression systems. Methodologies to predict how innovative fire suppression systems would perform for various fire scenarios are not available. An individual company will not develop and market a fire suppression system that is not certified via a nationally recognized listing organization (e.g., Underwriters Laboratories (UL), FM Global).

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** Properly characterizing ignition, flame spread, fire growth, flashover, and smoke spread in a building fire requires the clever design of experiments to measure temperature, heat flux, gas phase and condensed species, velocity and heat release rate under controlled laboratory simulations of almost endless possibilities of furnishings and room geometries. Add to that requirement the need to measure the release of the suppressant, its concentration and phase, the transport of material to the fire, and the interactions that lead to local extinguishment and full suppression. The result is that reliable prediction of the performance of the system, which is required to extrapolate beyond the test to the field, becomes a daunting task.

***Potential Solutions to Measurement Problem*:** Devise a subset of fire scenarios (fuel load, fuel type, ventilation, and geometry) that spans the range of conditions seen in actual building fires and conduct an array of benchmark experiments (fire alone, suppression system alone, suppression system interacting with fire) in which the flame spread and fire growth, suppression agent discharge and the reduction in heat release due to the interactions between the fire and suppressant can be measured, for the purpose of developing a database against which computational models can be refined. Demonstrate the ability of these models to predict, in qualitative terms, the probability that a given system will successfully suppress a given fire in a given structure.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** Construction Life-Cycle Software Systems Interoperability

***Submitter*:** Kent Reed

***Technological Innovation at Stake*:** The U.S. building and construction industries are seeking to become more competitive through the use of interoperable computer-aided systems throughout the construction lifecycle (e.g., engineering, architecture, fabrication, manufacturing, construction, maintenance, and operations software systems). It is increasingly difficult to ensure the interoperability of these systems as they are introduced into more work processes in design, construction, operation, and emergency response. Current standards for the representation and interchange of information among these systems are not sufficient.

***Economic Significance of Innovation*:** Interoperability can yield greater productivity and higher quality work without compromising worker safety. The U.S. capital facilities industry is losing $15.8B each year because of inadequate interoperability of its software systems. In addition, the lack of the means to demonstrate interoperability impedes the introduction of innovative software to the industry.

***Technical Barrier to the Innovation*:** The lack of objective performance based standards to quantify interoperability throughout the construction lifecycle is needed. Customary approaches to comprehensive software testing are handcrafted and impose such a burden in time and cost that they are rarely applied. In conformance and interoperability testing, the approach has been to demonstrate success with a few exemplary cases. This does not translate into successful interchange of information throughout the lifecycle of a building. Automated test methods and evaluation procedures are needed to quickly and economically assess conformance and interoperability of software products.

***Stage of Innovation Where Barrier Appears*:** Marketing, End Use

***Measurement-Problem Part of Technical Barrier*:** New measurement science research (to determine performance of automatically generated tests) is needed to enable comprehensive automatic test generation for large-scale software systems with respect to equally large-scale information content standards. Cost-effective test methods and evaluation procedures that can provide quantitative measures of the adequacy of the commercial implementations of these standards in will ensure interoperability.

***Potential Solutions to Measurement Problem*:** Basic research is needed to establish the missing measurement science. Applied research is needed to establish measurement technologies based on the measurement science. It is this technology that will itself become the subject of open standards that ensure its successful promulgation.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** Construction Automation Tools

***Submitter*:** Jim St. Pierre

***Technological Innovation at Stake*:** Development of life-cycle integrated information systems required for construction site automation. Such systems are needed in order for design information to flow error-free to automated equipment, such as robotics, at the construction site. Use of life-cycle integrated information systems by engineers, architects, construction personnel, and building owners will lower costs associated with constructed facilities through reductions in on-site fabrication time, construction errors, and job-site accidents.

***Economic Significance of Innovation*:** According to the 2002 Census the value of structural steel erection work done in the U.S. was $8B. The value of concrete contractors work done was $26B. The American Institute of Steel Construction (AISC) has stated the need for a 25% reduction in time to erect a steel frame structure (from design to erection). A 25% reduction in steel construction time through greater use of automation could significantly decrease costs. Other types of construction could reap similar benefits.

Technical Barriers to the Innovation: The problem for the construction industry is that the information supplied and required at the field level has multiplied, but traditional manual processes are still in effect. The field level (i.e., at the construction site) application of technology to process this information doesn't exist today, which limits the effectiveness and productivity of all facets of construction execution. Many construction practitioners have tried to implement such technologies in one of their projects, without the benefit of extensive product comparisons, careful performance-based selection, pilot testing, and careful measurements of return on investment, only to see their costs go up and their productivity go down.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Methodologies and metrics (e.g., accuracy, interoperability of the software design representations – models – throughout the lifecycle) are needed to measure the performance and productivity enhancements of construction automation and data transfer, in order to demonstrate to end users the benefits of adopting these technologies. The methods and metrics must identify and quantify all life-cycle cost and performance benefits as well as data integrity, accuracy, precision, consistency and interoperability, and other parameters which can impact productivity.

***Potential Solutions to Measurement Problem*:** Develop the performance-based metrics required to implement the Intelligent Automated Construction Job Site (IACJS) of the future envisioned by the FIATECH roadmap.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Laser-based 3D Imaging Systems

***Submitter*:** Alan Lytle and Gerry Cheok

***Technological Innovation at Stake*:** Laser-based 3D imaging systems (e.g. laser scanners, 3D range cameras, flash LADARs, etc.) are instruments used to rapidly capture 3D information of a scene or object. The 3D information captured by these systems is a collection of measured points which is referred to as a 'point cloud'. These point clouds may contain hundreds of thousands of 3D points from a single scan. This technology could fundamentally change large scale metrology as applied to capital construction projects and enable measurable improvements in project delivery. The ultimate benefits would include shorter delivery schedules and improved quality.

***Economic Significance of Innovation*:** 3D imaging systems are increasingly being used to capture existing conditions on capital construction projects. The construction sector accounts for approximately 80 % of the market for 3D imaging systems, where the ability to rapidly capture and assess existing conditions is providing work process improvements in such areas as increased bid accuracy, reduced installation errors and rework, and better quality control of fabricated materials. From case studies it is estimated that although the direct cost savings of 3D imaging over conventional surveying (10 % - 20 %) is small compared to the total cost of the project, the ability to provide substantially more data in shorter time provides up to 5 % - 10 % savings of the total project through such means as rework reduction and schedule shortening. With the value of construction put in place annually at approximately 5 % - 10 % of the US Gross Domestic Product, these small percentages amount to significant potential monetary savings for the industry as a whole.

***Technical Barrier to the Innovation*:** There are currently no standard test methods for evaluating the performance of 3D imaging systems nor their end products derived from the data. This lack of standard test methods is inhibiting a wider market acceptance of these systems in the construction and manufacturing sectors. Market penetration in the transportation sector – where this technology is viewed as a critical enabler for unmanned vehicles and driver assist safety systems – is also limited by the lack of standard testing protocols.

***Stage of Innovation Where Barrier Appears*:** Marketplace

***Measurement-Problem Part of Technical Barrier*:** Development of specific test protocols for analyzing 3D system imaging performance. Development of analysis techniques to characterize uncertainty of geometric models derived from 3D image data.

***Potential Solutions to Measurement Problem*:** Research and development to provide open, consensus-based standard test methods for the performance and use of 3D imaging systems.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Egress Performance Models

***Submitter*:** R. Peacock and J. Averill

***Technological Innovation at Stake*:** Egress flow models are needed in order to construct taller and larger buildings. Current design practice utilizes prescriptive, rather than performance based, building codes. Prescriptive codes define egress requirements based on the occupants on a single floor independent of the overall height of the building. The safety and economics of innovative building designs cannot currently be assessed due to limitations inherent in current egress models. While there are dozens of models to simulate the evacuation of occupants from a given building geometry, there is limited contemporary data to support the model inputs or assumptions and even less information available to validate the models for actual emergencies. Collection and analysis of such data would provide a basis for performance-based building code requirements, the practice of egress system design, and ensure robustness for analysis of emerging issues.

***Economic Significance of Innovation*:** The inability to reliably determine the necessary design capacity for emergency evacuation from buildings has a two-fold economic impact. First, prescriptive over-design of egress systems in buildings reduces available rentable space, increasing cost to occupants over the entire life cycle. For example, inclusion of an additional stairway which may not add to occupant safety can consume 10 m^2 of rentable space per floor, which at $500/$m^2$ in a typical commercial district would cost $250 K/yr in a 50 story building. Of even greater importance is the second impact, caused by under-design of the egress systems, which can lead to tragic loss of life and injury. Fire statistics for 2004 show more than 3 000 deaths and 15 000 injuries occupied in structure fires.

***Technical Barrier to the Innovation*:** Lack of contemporary data precludes realistic evacuation calculations during the design stages of a building. Further, a lack of specific performance objectives creates disincentives to provide other than prescriptive-consistent (i.e., minimal) egress capacity. Current prescriptive code requirements base egress capacity on single-floor loads, independent of the number of stories, which can lead to multi-hour evacuation times for tall buildings. Finally, current methods of data analysis are extremely time-consuming and costly since they depend on multiple passes through the videos to record timing and actions for each occupant in the evacuation.

***Stage of Innovation Where Barrier Appears*:** End Use

Measurement-Problem Part of the Technical Barrier: Research is needed to develop the relationship between stairway width and evacuee flow or stochastic functions for human behaviors in emergencies, including human interfaces with egress technologies (i.e., elevators designed for evacuation use).

***Potential Solutions to Measurement Problem*:** R&D to systematically collect building evacuation data, in order to establish a scientific foundation for numerical assessment of building evacuation models used during the design stage. Collection of data such as occupant movement speeds as a function of environmental constraints, human behavior, emergency management, means of egress construction, and occupant effects of toxic products, could provide a sound theoretical and engineering foundation for timely escape from the built environment in the United States.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*: ** Fire Detection Systems

Submitter: Thomas Cleary and William Davis

***Technological Innovation at Stake*:** Fault-free, multi-functional fire detection systems, equipped with combination sensors, advanced video detection, intelligent signal processing, and integrated security systems have the potential to vastly improve fire detection and security in commercial/industrial and residential applications.

***Economic Significance of Innovation*:** The fire alarm and related security industry have annual sales of products and services of about $18B in 2002. The adoption of innovative fire/theft detection technologies could reduce annual U.S. fire ($10B in 2004) and theft ($30B in 2004) losses. This can then translate to reduced insurance premiums for consumers. U.S. businesses will also benefit from reduced damages can through early intervention.

***Technical Barrier to the Innovation*:** Measurement standards fail to exist that demonstrate the benefit of innovative fire and theft detection approaches against a wide range of fire and intrusion scenarios. The lack of measurement standards and national certifications through UL and Factory Mutual (FM) impedes the introduction of innovative fire/detection systems into the marketplace.

***Stage of Innovation Where Barrier Appears*:** Marketing

***Measurement-Problem Part of Technical Barrier*:** Properly capturing the physical parameters that characterize an actual fire, and the probable nuisance sources (dust, condensation, cooking fumes, etc.) that could plague the system, requires the clever design of experiments and measurements of velocity, gas composition, particulate matter, temperature, heat flux, and electromagnetic radiation from the UV to the mid-IR, all under conditions that are less-than-pristine. Once likely fire and nuisance sources are characterized, robust and unbiased measurement methods and performance standards need to be developed against which alternative technologies can be assessed under conditions representative of those source.

***Potential Solutions to Measurement Problem*:** Detailed measurements during the early stages of test fires and nuisance sources can be made in laboratory settings. A fire emulator/detector evaluator has been developed to provide a way to test multi-sensor fire detectors and provide a performance assessment against benchmark fire scenarios and nuisance sources. A parallel approach is required for volumetric sensors such as video imagers. The integration with security systems and performance of the software can be adapted to the existing virtual cybernetic building test bed.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Models for Fire Spread and Growth on Objects

***Submitter*:** John L. de Ris , FM Global, William M. Pitts

***Technological Innovation at Stake*:** Current design practice for fire safety in structures and their contents is empirical and experience based. As a result, expensive and time-consuming tests are required during the design and certification phases of product development and when new construction designs and/or approaches are be used. The availability of validated models for fire growth and spread would allow faster and cheaper product design and more innovative and cost effective building design and construction.

***Economic Significance of Innovation*:** The availability of models for fire spread and growth on objects with sufficient accuracy for design purposes will result in significant reductions in the time and cost required for manufacturers to design and test new products. This capability will also allow manufacturers to respond more efficiently to product modifications necessitated by regulations (e.g., banning the use of certain fire retardants). The lack of effective models for fire spread and growth is a major roadblock to the ongoing efforts to shift from prescriptive- to performance-based fire codes. This shift is intended to allow technical innovation in building design and construction, while reducing building costs. The lack of understanding of fire spread leads to uncertainties in insurance underwriting and increases costs.

***Technical Barrier to the Innovation*:** The development of fire spread and growth models requires an understanding of the heat transfer taking place from a growing fire to nearby burning and non-burning fuel surfaces. The absence of experimental approaches capable of characterizing the heat fluxes (conductive, convective, and radiative) responsible for heating the fuel near a growing fire is the major barrier limiting the understanding of fire growth and spread, and thus for developing models describing the process.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The development of the fundamental understanding of fire spread and growth on objects is impeded by the lack of heat flux measurements, which inhibits the development of the engineering models. The measurement need is an experimental diagnostic capable of determining the heat flux into burning and non-burning material located adjacent to a spreading fire.

***Potential Solutions to Measurement Problem*:** Solution of this problem may be possible by an improved understanding and use of existing instrumentation. Most current measurement approaches are based on measuring temperature differences across surfaces undergoing heat transfer and are subject to a wide range of errors and uncertainties. On the contrary, the development of a new approach based on different principles (such as burning in different atmospheres) may be required.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** High Performance Thermal Insulation

***Submitter*:** Therese K Stovall, Oak Ridge National Laboratory, and Robert Zarr

***Technological Innovation at Stake*:** Insulation technologies are being developed to reduce the energy consumption associated with refrigerators, freezers, and the transport of refrigerated products. Among the concepts being developed are powder, foam, and glass-fiber filled evacuated panels, low conductivity gas-filled panels, and aerogels. These advanced insulation panels offer the potential for significant reductions in energy consumption and greater flexibility in product design. These advanced insulation products offer thermal resistance to heat flow an order of magnitude greater than conventional insulation materials.

***Economic Significance of Innovation*:** As energy costs increase, advanced insulation materials will become more cost-effective, as demonstrated by their broad use in Europe and Japan. They have significant energy conservation potential in residential appliances and temperature sensitive shipping applications, such as refrigerated trucks. Early adopters include laboratory refrigerators, medical shipping containers, recreational vehicles, and the space shuttle.

***Technical Barrier to the Innovation*:** Many vacuum insulation products are non-homogenous and require the use of mathematical models, supported by multiple measurements, to determine their overall performance. The inability to reliably and accurately define the thermal resistance of the insulation core limits the ability to accurately assess the overall product performance, and thus hinders product improvements.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The thermal performance of most insulation products is measured using a heat flux meter apparatus, as described in ASTM C518 Standard Test Method. This method is used because it is fast, reliable, and economical. However, this test method is a secondary test method, and requires the use of a certified calibration standard material. Currently, calibration standards fail to exist with thermal resistance values comparable to those associated with high performance insulation products. Faced with this deficiency, researchers currently improvise calibration methods that rely on both increased thicknesses of conventional insulation and reduced temperature differences, both of which introduce significant measurement uncertainties.

***Potential Solutions to Measurement Problem*:** The development and production of stable long-lived calibration standards with a thermal resistance comparable to those associated with advanced insulation products.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** Extreme ultraviolet reflective optics

***Submitter*:** Thomas Lucatorto

***Technological Innovation at Stake*:** Introduction of extreme ultraviolet lithography (EUVL) as the manufacturing process for the next generation semiconductor-based electronic products requires the use of extreme ultraviolet reflective optics.

***Economic Significance of Innovation*:** Semiconductor manufacturing is the largest US manufacturing industry, as measured by value added. The net economic benefit of innovation in US semiconductor manufacturing since 1974 is $260 billion per year. Advances in lithography are a key driver of innovation in this sector, delivering increases in the density of circuit components. Computer processors produced with EUVL technology are expected to be almost ten times faster than today's most powerful chips, and the storage capacity of memory chips will increase even more, having many downstream benefits.

***Technical Barrier to the Innovation*:** Current lifetime of EUVL reflective optics is more than a factor of 100 below what is required. EUV light, whose wavelength of ~10 nm is 1/50 that of green light, is strongly absorbed by all materials and can be imaged only by reflective optics. Since optimal resolution requires the figure of the optics to be within a fraction of the operational wavelength, EUVL optical components must be fabricated to sub-nanometer tolerances. Due to the high cost of both fabrication and replacement down-time, the optics must retain these tolerances for ~30,000 hours (3.4 years) of operation in a production environment. Current capabilities are less than 3000 hours.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The development of new, more durable reflective optics will not be possible without a reliable method of accelerated testing to predict the lifetime. A reliable method of accelerated testing includes EUV reflectivities certified at 10 nm wavelengths, dimensional measurements with sub-nanometer tolerances, and the development of stable and calibrated detectors for radiometry of intense, pulsed EUV light sources.

***Potential Solutions to Measurement Problem*:** Develop a facility to expose EUVL optics to high levels of EUV light under controlled environmental conditions, measure the microscopic mechanisms of component failure, and determine scaling laws to extrapolate optic lifetime.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Optical Scatterometry

***Submitter*:** Thomas A. Germer

***Technological Innovation at Stake*:** The continued shrinking of semiconducting devices is limited by the ability to accurately and tightly control device dimensions. Measurement of these dimensions performed by optical scatterometry has demonstrated high sensitivity and high throughput.

***Economic Significance of Innovation*:** The U.S. semiconductor industry (which employs 250,000 U.S. workers) relies upon ever-decreasing device sizes in order to help develop products that are cheaper, faster, and better and to maintain its competitive edge. While there are many factors affecting product device size, of which metrology is just one, any factor which limits it will seriously affect the industry's profitability. While the industry innovation is lead by U.S. companies, most of the commodity production is performed outside of the U.S. It is generally viewed that if or when device sizes plateau and it becomes a commodity, U.S. companies will no longer dominate the industry.

***Technical Barrier to the Innovation*:** Optical scatterometry has demonstrated high sensitivity and high throughput, but the accuracy is insufficient and results vary widely between different tools of different manufacturers.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Insufficient knowledge of the optical properties of the materials limits the existing capabilities and the development of fundamental theoretical models which severely limit the measurement accuracy.

***Potential Solutions to Measurement Problem*:** Improved measurement methods for determining the optical properties of materials used in semiconductor manufacturing and improved electromagnetic models for the properties of optical scatterometry.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Satellite-based optical calibration

***Submitter*:** Raju Datla

***Technological Innovation at Stake*:** The laboratory calibration of optical sensors to SI standards typically changes upon launch and continues to drift in the hostile space environment. The technological innovation of SI traceable standards for on-orbit calibration is required for research involving the assessment of long-term global climate change.

***Economic Significance of Innovation*:** Many questions arise concerning the earth's condition. Is the earth's climate changing? If so, at what rate? Are the causes natural or human-induced? Ensuring the accuracy of satellite measurements involved in addressing these questions is critical for obtaining scientific data with greater certainty. This in turn, can help create effective responses to climate change to minimize its impact on our economy and our quality of life.

***Technical Barrier to the Innovation*:** The requirements for the accuracy of satellite-based optical measurements exceed present capabilities. Since the laboratory calibration of sensors change under the extreme conditions of launch and space, it is difficult to tie satellite measurements to SI standards. Once the device is in space, no methods exist to re-calibrate. Assessing the magnitude of this change using a ground-based source is challenging because of the unknown effects caused by the atmosphere on the measurements.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Relatively stable celestial optical radiation sources such as the sun, the moon, and the stars can be measured from space as stable calibration sources; however, tying the celestial optical radiation sources to the NIST absolute radiometric scale is the measurement problem.

***Potential Solutions to Measurement Problem*:** A potential solution is overlapping simultaneous satellite observations of common earth and atmospheric sites that are independently calibrated using air and ground based SI traceable radiometry. Another solution is to develop a stable extraterrestrial object for common viewing by satellites irrespective of time and space. These objects include the moon, sun and stars depending on the spectral regions of interest.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Extreme ultraviolet lithography

***Submitter*:** John T. Woodward

***Technological Innovation at Stake*:** Introduction of extreme ultraviolet lithography (EUVL) as the manufacturing process for next generation semiconductor based electronics requires significant improvement in photoresist performance.

***Economic Significance of Innovation*:** Semiconductor manufacturing is the largest U.S. manufacturing industry, as measured by value added. The net economic benefit of innovation in semiconductor manufacturing since 1974 is $260 billion per year. Advances in lithography are a key driver of innovation in this sector, delivering continuing increases in the density of circuit components. EUVL is in development as the next-generation patterning technology, to attain critical manufacturing dimensions of 10 nm. Computer processors produced with EUVL technology are expected to be almost ten times faster than today's most powerful chips, and the storage capacity of memory chips will increase even more, yielding many downstream benefits.

***Technical Barrier to the Innovation*:** A line width roughness (LWR) of 1.5 nm is required for features at the 32 nm node at which EUVL is anticipated to be introduced by the International Technology Roadmap for Semiconductors. Current generation photoresists have LWR that are more three times this when exposed with a commercially viable EUV dose ($\leq$ 5 mJ/cm^2).

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The photolithographic process consists of a series of chemical modifications to the photoresist that ultimately result in the development of the pattern through chemical dissolution at which point it is imaged by SEM. There is no analytical technique that is capable of resolving the chemical changes during the lithographic process prior to development. Thus it is not known what stage of the process is contributing to the LWR.

***Potential Solutions to Measurement Problem*:** Develop chemically functional scanning probe microscopy as a quantitative metrology with nanometer scale spatial resolution and required chemical sensitivity.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Energy-Efficient lighting

***Submitter*:** John Curry

***Technological Innovation at Stake*:** Next generation High Intensity Discharge (HID) lamps have the potential to double the efficiency of any general lighting product that is currently available.

***Economic Significance of Innovation*:** According to the Department of Energy (DOE), lighting accounts for 8% of all energy consumption in the United States and 22% of electricity nationwide. Next generation HID lamps have the possibility of doubling in efficiency which would significantly reduce electricity consumption. Additionally, 40% of lumen market is turned over annually, so any acceleration of technology will be implemented quickly and will yield large economic impacts.

***Technical Barrier to the Innovation*:** Improved modeling of discharges in HID lamps is needed to improve their efficiency. Present spectroscopic data from high-intensity discharge lamps are inadequate to validate lamp models. Information is needed for atomic energy levels, spectral line identification, and transition probabilities for materials of interest to the lighting industry.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Reliable spectral measurements for chemical species of interest found in the high intensity discharge are needed to interpret the optical spectra of such lamps. Not only required are the methods to make the measurements but an HID database of the absorptions for the species of interest.

***Potential Solutions to Measurement Problem*:** The development of x-ray and optical spectroscopic techniques to determine plasma temperature and distribution of species in the plasma will provide the information for the HID database.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Single molecule optical measurement

***Submitter*:** Lori Goldner

***Technological Innovation at Stake*:** The ultimate limit of all nanobiotechnology is the ability to follow a bioreaction on a single molecule scale which requires optical detection and measurement of single molecules. This ability makes the optical detection and measurement of rare species possible and can revolutionize the basic understanding of biological and biochemical processes, and thereby advancing the understanding of cellular activity and treatment of disease.

***Economic Significance of Innovation*:** The ability to make single molecule measurements eliminates the waste of expensive resources and reduces to a minimum the need to deal with harmful or toxic substances. Significant reductions in time and costs can be realized by using single molecule measurement techniques to replace laboratory processes that require amplification such as polymerase chain reaction (PCR). Reduction in costs and damage to the environment can be achieved by minimizing the use of expensive chemical reagents, which may pose significant health hazards when used in greater than trace quantities.

***Technical Barrier to the Innovation*:** Isolation, immobilization (when necessary), and chemical labeling of the species under investigation are the primary technical challenges facing industry regarding the use and reliability of single molecule measurements.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Nanoencapsulation and labeling schemes that are minimally perturbative to a single molecule or a single nanobiosystem such as a molecular complex, virus, or organelle are needed. A good nanoencapsulation system will not change the functionality of the molecule or nanobiosystem under test. Determining the magnitude or the degree of perturbation requires research into measurement methods and technologies.

***Potential Solutions to Measurement Problem*:** Nanoencapsulation schemes involving water-in-oil reverse emulsions and liposomes are possible and should be physically investigated. Current labeling schemes involve commercial dyes. New fluorescent species and analogs and optically detectable nanoparticles are alternatives that can increase sensitivity, therefore reducing the concentration of nanoparticles required. In some cases, comparison of single molecule and traditional bulk experiments can be used to investigate degree of perturbation and optimize single molecule technique. In other cases, direct investigation and modeling of single molecule dynamics can be used to validate these techniques.

***Technology at Issue*:** Brachytherapy dosimetry

***Submitter*:** Michael Mitch

***Technological Innovation at Stake*:** Brachytherapy is an advanced cancer treatment where radioactive seeds or sources are placed in or near the tumor itself, delivering a high radiation dose to the tumor while minimizing the radiation exposure in the surrounding healthy tissues.

***Economic Significance of Innovation*:** An absorbed-dose-rate standard for radioactive sources used in brachytherapy, e.g., for treating prostate cancer, could expand the utility of low-energy photon sources in treating cancer and other diseases. This technology makes cancer treatment more effective (reduces morbidity/mortality) and the consequential improved health effects can significantly reduce cancer treatment cost.

***Technical Barrier to the Innovation*:** The development of a dosimeter capable of functioning as a primary standard for absorbed-dose-rate measurements of low-energy-photon-emitting brachytherapy sources is required. Apparatus currently used to measure absorbed dose (i.e., ionization chambers) do not have the sensitivity or spatial resolution to calibrate low-energy-photon-emitting brachytherapy sources. To accurately measure absorbed-dose distributions around brachytherapy sources, we need a detector small enough so that the dose does not vary significantly over the active volume, but large enough to obtain a strong enough signal; the material should be water (tissue) equivalent in its response to low-energy photons, and should be useable in a water phantom.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** No dosimeters are currently available capable of measuring absolutely the absorbed dose-in-water of low-energy-photon-emitting brachytherapy sources with sufficient accuracy to be useful as a standard. The problem with making accurate dose measurements for such sources is that the dose changes rapidly over short distances and the intensity of the emitted radiation is relatively weak. This leads to conflicting requirements that in existing dosimetry instrumentation are not simultaneously satisfied, since to achieve a detectable signal, the size of the detector element is too large to achieve the required spatial resolution.

***Potential Solutions to Measurement Problem*:** Develop a dosimeter capable of directly realizing the absorbed dose in water at a reference point near low-energy-photon-emitting brachytherapy sources. In addition to being made of water-equivalent materials, the detector element would have to be on the order of 0.5 mm in all three dimensions, and be coupled to a system capable of achieving an acceptable signal to background ratio, as well as be able to measure the relative dose distribution around brachytherapy sources with high spatial resolution.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Infrared Signatures

***Submitter*:** Gerald T. Fraser

***Technological Innovation at Stake*:** Identification of military targets, such as ground and aerospace vehicles, through the use of infrared (IR) signatures is critical for defense and homeland security. Infrared signatures are used to detect, identify, and track vehicles for reconnaissance, surveillance, and targeting. The signatures of vehicles are used to assess their detectability by adversaries, and are thus specified in Department of Defense's (DoD) acquisition of new vehicles, coatings, and camouflage.

***Economic Significance of Innovation*:** Research in improving the ability to detect, suppress, and model IR signatures is primarily targeted at defense applications leading to technologies such as thermal imaging cameras, IR scene projectors, night-vision equipment, IR stealth coatings, and IR countermeasures. However, spin-offs of these technologies are increasingly finding civilian applications in homeland security (security systems, fire and rescue, chemical agent detection, border protection, civilian airplane antimissile protection), energy efficiency assessment (IR thermography), automobiles (night vision), and quality control in manufacturing (IR inspection, chemical spatial mapping of materials).

***Technical Barrier to the Innovation*:** The thermal radiation from the target must be measured as a function of target orientation, and include corrections for atmospheric absorption and emission and the thermal background radiation. First-principle modeling of signatures requires a sophisticated radiative transfer computer code based on the detailed structural model of the target, including all facets, surface types, and coatings. The optical and thermal properties of each structural element must be known. Optical properties consist of the surface reflectivity as a function of illumination and viewing angle, temperature, wavelength, and surface temperature. Presently, neither measurements nor models are sufficiently accurate to predict target signatures under the variety of scenarios realized in an operational setting.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** IR signature measurements between different test sites and different types of test sites do not agree. Facilities need IR standards with known signatures, standardized measurement methods, absolutely calibrated and stable IR imagers, independently sponsored measurement comparisons, and validation against rigorous modeling. The latter requires accurate data on the optical properties of materials which is lacking. Standards to ensure that suppliers of such data are proficient in the measurements or modeling are essential.

***Potential Solutions to Measurement Problem*:** 1. Standard artifacts consisting of structural elements with known thermal and optical properties; 2. Rigorous sample uncertainty analyses validated by comparisons between test sites for different types of signature measurements and targets; 3. New instruments which can perform optical measurements rapidly and accurately, including temperature and polarization dependencies; 4. Large optical properties databases populated with accurate materials properties; 5. Instruments to accurately characterize the atmospheric absorption and thermal background; and 6. Infrared imagers with improved environmental stability and temperature measurement accuracy.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Proteomes Mass Spectrometry

***Submitter*:** David Plusquellic

***Technological Innovation at Stake*:** Mass spectrometry is emerging as the preferred method for characterizing proteomes. Proteomics, the large-scale study of the structure and function of proteins, is critical to understanding biological processes. Proteomics is instrumental in biomarker discovery, which is an indicator of a particular disease state or a particular state of an organism, and so has direct therapeutic application to improving human health. The industrial sector makes use of this technology in the development of new drugs and disease therapies.

***Economic Significance of Innovation*:** Mass spectrometry has emerged as the preferred method for characterizing proteomes. Instrument sales are predicted to reach $1.5 B by 2008. Different groups studying the same sample, even on the same instrument, commonly reach radically different conclusions concerning the proteins present in a sample. A good example comes from a recent Human Proteomic Organization study involving five laboratories. The combined results from all laboratories included a total of 1664 proteins identified in a serum sample. However, only 489 (29 %) of that total were identified by any two laboratories, and a mere 82 (5 %) were identified by all five. These inconsistencies cause a significant amount of time and money to be spent on multiple measurements.

***Technical Barrier to the Innovation*:** The operating conditions of mass spectrometers are insufficiently characterized to develop reliable fragmentation models. The physical origins of the variability in these measurements arise from the kinetics and dynamics of the buffer gas collision process and the variety of conformations and charge states that the peptide ions and clusters adopt. While methods exist for predicting fragmentation for a peptide sequence as well as its variability with instrumental conditions, in practice the operating conditions of spectrometers are insufficiently characterized to develop reliable fragmentation models.

***Stage of Innovation Where Barrier Appears*:** Marketplace

***Measurement-Problem Part of Technical Barrier*:** The measurement issue is one of developing transfer standards that can ensure cross-instrument reproducibility without introducing adverse effects to the operation of the instrument. The availability of this type of standard will permit reliable calibration and quality control to be conducted in each proteomic analysis, capabilities required to enable repeated use of reference data and to assure the quality of results. This will allow measurement reproducibility at the same level as available in gas chromatography/mass spectrometry, which is widely accepted as the best method for identifying volatile compounds.

***Potential Solutions to Measurement Problem*:** Known fragmentation patterns for specific peptide ions are needed to serve as internal standards, supporting protein identification. The peptide could be the natural product from the digestion of a proteome or added as a spike. Investigating the fragmentation of known peptide ions at known temperatures and in known configurations will provide a comparable molecular-level understanding for peptide ions.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue**:** Water Calorimetry for Clinical High-Energy Beams

Submitter**:** Heather Chen-Mayer

Technological Innovation at Stake**:** The technology at stake is a newly designed water calorimeter that incorporates innovative signal-processing techniques in time and frequency domains, is more efficient, robust, and precise. This instrument will be more suitable to directly measure and calibrate high-energy x-ray, electron, and proton beams as used in therapy with calorimetric-based dosimetric methods. Currently all ion chamber calibrations are transferred from ^{60}Co gamma rays, whose use in actual therapies has long been replaced by clinical accelerators.

Economic Significance of Innovation**:** NIST provides primary standards for radiation dosimetry needs for the more than 1800 radiation therapy clinics serving over 750,000 cancer patients a year in the U.S. Direct calibration in clinical beams eliminates reliance on ^{60}Co sources and the complicated transfer calculations, reducing the time required of clinical physicists and providing increased safety in dose delivery.

Technical Barrier to the Innovation**:** The technical barrier of developing and operating room-temperature water calorimeters is systematic errors due to heat transfer artifacts, leading to inferior standard measurements. Other concerns may arise from future applications to particle beams due to the nature of the radiation interaction with matters. An inaccurate primary reference standard impacts the entire industry as it propagates through the calibration coefficient of the ionization chambers.

Stage of Innovation Where Barrier Appears**:** R&D

Measurement-Problem Part of Technical Barrier**:** Systematic errors due to heat convection and conduction in the water calorimeter need to be determined. Identification (and elimination) of heat-transfer artifacts in room-temperature water calorimeters permit development of more compact and portable primary standards. This will benefit standards and metrology labs, which provide calibration services, and assist research into innovative dosimetry technologies, such as non-invasive temperature sensing, for which heat transfer artifacts hinder development of alternative standards.

Potential Solutions to Measurement Problem**:** Other metrology labs eliminate convection artifacts by refrigerating the water to 4°C (where the derivative of the density with respect to temperature is zero) and derive corrections to their data for conduction artifacts from finite-element analysis. By examining the frequency response of the system in both space and time, we are able to employ digital filtering techniques to quantify and eliminate conduction artifacts, enabling measurements at room temperature without requiring refrigeration. We will attempt to adapt these techniques for treating artifacts arising from natural convection, should they be observed.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Nanocrystal Biophotonic Sensors

***Submitter*:** Jeeseong Hwang and Kimberly Briggman

***Technological Innovation at Stake*:** The technology at stake is a variety of biocompatible luminescent nanocrystals (NCs) tailored with a number of unique optical and physical properties beyond the limitations of conventional organic probes used in a number of biomedical applications. NCs enhance and/or exhibit stronger optical signals than conventional organic tags and have a much longer shelf life.

***Economic Significance of Innovation*:** The NC industry is rapidly growing in the U.S. market: according to a new report, sensors designed and built using nanotechnology will generate global revenues of $2.7 billion in 2008 and reach $17.2 billion in 2012. Needs of NCs are rapidly growing in basic biomedical research (flow-cytometry and parallel biodetection assay), diagnostics (in vivo imaging, chemical sensors, and biomarkers), and clinical treatment (eradication of cancers and detection/destruction of pathogens).

***Technical Barrier to the Innovation*:** Despite the excellent photochemical and physical properties of NCs, the optical (fluorescent, scattering etc.) properties of NCs have been observed to be strongly dependent upon their nano-environment. For quantitative applications, a complete understanding of the physical and optical characteristics of NCs on a variety of biomimetic parameters is essential. The following technical needs are identified: (1) a platform to fabricate NC samples containing many environmental variables for the rapid characterization; (2) a set of new tools to quantitatively correlate optical properties and chemical or physical conditions of NCs in a controlled environment; and (3) measurement strategies and standards to assess NC properties when they are delivered into cells, tissues, and organisms.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The primary measurement challenge towards quantitative clinical and in vivo applications is significantly enhanced knowledge of the dependence of optical characteristics and chemical properties (change in surface functionalities, release of substances that cause toxicity, etc.) of NCs on a set of biomimetic parameters such as buffer pH, ionic concentration, and linkers and surfactants used to cluster or disperse the NCs.

***Potential Solutions to Measurement Problem*:** (1) Reference specimens: A microarrayer to dispense picoliters of nanosensor solution onto a functionalized substrate with high-accuracy positioning capability is an ideal tool to produce arrays of a few hundred to thousand combinatorial nanosensor spots on one sample substrate with biomimetic parameters varied at different sample spots. (2) Simultaneous optical and physical characterization: Chemical sensing microscopy combined with optical spectroscopy will provide nanoscale chemical details of the NC surfaces to be correlated with optical characteristics. (3) Dynamic evaluation of in vivo delivery effect: Multi-dimensional chemical and optical imaging (vibrational spectroscopy, fluorescence lifetime measurements, etc) will not only characterize NCs themselves, but allow them be employed as nanosensors to probe local in vivo environment.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Rare Gene Microarray Detector

***Submitter*:** Jeeseong Hwang

Technological Innovation at Stake: The technology at stake is the use of microarray techniques as a unique solution to achieve high throughput screening of rare genes (DNA and RNA) involving human diseases and infectious pathogens and microbes. The increase of the diversity of test sequences and well-behaved target/probe interactions of genes will allow the design of fully informative assays.

***Economic Significance of Innovation*:** As reliable detection of single pathogenic species and rare transcripts is becoming feasible, enhancement of microarray techniques will allow us to look at many targets in parallel for rapid diagnosis and effective response to infectious diseases, naturally occurring epidemics, and bioterrorist attacks. For instance, prevention of water- and food-borne infections is possible by effective identification of causes. In battling against rapidly spreading infectious diseases, the misuse of antibiotics and the lack of new antibiotic and antiviral agents have increased the risk of more serious infections. Differential diagnosis of infections will enable rational and effective drug therapy.

***Technical Barrier to the Innovation*:** Technical barriers to rare gene microarray detectors include identification of rare genes and development of validation standards for screening methods of clinically relevant genomic templates for the detection of rare genes.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Identification of rare genes is required and to detect rare genes and pathogens (ultimately at the single copy level), sensitivity and accuracy need to be improved to overcome current limitations. Additionally rapid validation of screening methods to establish clinically applicable assays and methods to effectively isolate, extract, and concentrate samples for a microarray platform are required.

Potential Solutions to Measurement Problem: To enhance sensitivity, accuracy, and speed of the technique, assays employing novel fluorescent probes have been proposed and under development. Several novel probes have been identified to have unique optical and physical properties that overcome the limitations of conventional probes. BioMEMS-based technique is rapidly evolving and may be instrumental either to allow effective sample preparation for the conventional microarray platform or to enable fully integrated a lab-on-a-chip assay. For the validation of screening methods for clinical applications, standards to correlate between clinical diagnostics and screening results need to be established.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Ultraviolet and Vacuum Ultraviolet Standards

***Submitter*:** Ping-Shine Shaw

***Technological Innovation at Stake*:** Standards for detector and source calibration in the ultraviolet and vacuum ultraviolet are required for a wide range of industrial applications such as semiconductor device fabrication, curing industry, water purification, medical treatments and environmental monitoring. In the semiconductor industry, the light source used for photolithography is shifting from ultraviolet well into the vacuum ultraviolet. With such vast applications, radiometric support for detector and source standards is critical for future development in these industries.

***Economic Significance of Innovation*:** One example of maintaining national standards in the ultraviolet and vacuum ultraviolet is the increased efficiency in photolithography for the fabrication of electronic devices. Standards also will improve efficiency for the curing industry by lowering the product manufacturing cost. Maintaining a standard helps manufacturers of detectors and sources to ensure their product quality.

***Technical Barrier to the Innovation*:** The detectors and materials currently used for visible light measurements prove to be unstable when used with ultraviolet and vacuum ultraviolet radiation. The ultraviolet and vacuum ultraviolet radiation gradually degrade the chemical nature of semiconductor structure leading to variation in detector responses that increase uncertainty in radiation measurements.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The measurement problem is characterizing the stability and the failure mechanisms of the detector materials. A calibration and characterization facility for new prototypical detectors is required that is based on stable ultraviolet and vacuum ultraviolet sources.

***Potential Solutions to Measurement Problem*:** Several techniques are used to improve the stability of silicon photodiodes, including nitrided silicon oxide or platinum silicide front window. Additionally, semiconductor materials other than silicon have been used. By developing a calibration and characterization facility using equipment such as synchrotron radiation sources, blackbody sources and cryogenic radiometers as the basis for the development of radiation standards in the ultraviolet and vacuum ultraviolet regions the properties of these materials can be tested and improved.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue**:** Fusion Energy Reactors (Tokamaks)

Submitter**:** Joseph Reader

Technological Innovation at Stake**:** A tokamak is a torus-shaped device utilizing magnetic confinement of extremely hot plasma and is the leading candidate for producing fusion energy. Scientists have produced 16 megawatts of fusion power in the laboratory and have studied the behavior of fusion products in burning plasmas. Underlying this progress are strides in fundamental understanding, which have led to the ability to control aspects of plasma behavior.

Economic Significance of Innovation**:** Abundant and affordable energy is essential to a healthy and vigorous industrial society and is a critical factor in improving the standard of living in developing countries. The rising cost of energy has already slowed the economies of all nations. It is increasingly clear that human progress and the survival of future generations depends upon developing an energy source that is limitless and safe, as well as environmentally and economically attractive. Fusion can be that energy source.

Technical Barrier to the Innovation**:** The atomic data needed to understand radiation from the plasma and other fundamental processes occurring in a tokamak are often unavailable or of poor accuracy. The atomic data is need to monitor the status of the plasma and the materials that are extracted from the surroundings, such as the walls, that are not to be part of the fusion process.

Stage of Innovation Where Barrier Appears**:** R&D

Measurement-Problem Part of Technical Barrier**:** The accurate measurement of wavelengths and transition rates for a wide range of atomic species used in various wall materials is difficult. As the tokamak-relevant spectral lines are generated only in very hot plasma, the laboratory measurements require conditions similar to those inside an operating tokamak, which are difficult to create and sustain.

Potential Solutions to Measurement Problem**:** Develop small-scale plasma devices capable of generating extremely hot plasmas that would be used for spectroscopic measurements. Once collected, the spectroscopic data must be disseminated in critically-evaluated compilations and in on-line databases.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue**:** Industrial use of high current electron beams

Submitter**:** Anthony Berejka, Ionicorp[+]

Technological Innovation at Stake**:** New applications for electron beam processing continue to grow. Electron beam processing effectively and efficiently creates useful changes in material properties and performance, such as polymer crosslinking and chain scissioning. Electron beam processing is widely used for medical device sterilization, cosmetics sterilization, and pharmaceutical sterilization. However, the effective dose on the material is unknown.

Economic Significance of Innovation**:** Electron beams processing involves diverse industrial segments that cumulatively exceed several $100 B in product value. Electron beams processing is an accepted practice in the manufacture of tires, wire and cable, shrink tubing and film, and in the drying and curing of coatings and inks. Emerging areas of opportunity, such as the sterilization of medical devices and decontamination of food, lack a coherent measurement system related to high current accelerators based upon appropriate measurement techniques. Unlike gamma irradiation, which involves the use of a radioactive Cobalt or Cesium source, electron beam technology does not produce radioactive materials that need disposal.

Technical Barrier to the Innovation**:** Existing protocols are unrelated to the effective dose for accepted industrial use of high current, high product through-put electron beam processing systems. The protocols characterize the output of the source, and not the interaction with the material.

Stage of Innovation Where Barrier Appears**:** Marketplace

Measurement-Problem Part of Technical Barrier**:** Accurate and reliable measurement techniques are needed to characterize material exposure from high voltage electron beam accelerators (up to 10 MV) at high beam currents (>10 ma) and from low voltage accelerators (80 to 300 KV), which are used in environmentally benign processes operating at process rates as high as 300 m/minute.

Potential Solutions to Measurement Problem**:** Alanine, an amino-acid, has been acknowledged as the most precise material for characterizing electron beam exposure. Films coated with alanine are now produced by a reputable film manufacturer. Spin resonance signals related to exposure intensity can be read on instruments that have an internal reference marker. These have been used in developing the e-calibration system by NIST to provide Internet/telecom based calibration services. Standard reference data are needed based upon determining alanine marker ratios from exposures to high current electron beam sources at voltages between 80 KV and 10 MV and beam currents >10 ma and at industry acceptable process rates, as high as 300 m/minute.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Biodosimetry

***Submitter*:** Anthony Berejka, Ionicorp[+]

***Technological Innovation at Stake*:** Ionizing radiation is used to decontaminate and sterilize biohazards found on products such as medical products, food and foodstuff, and mail as was found in the recent anthrax contamination. However, the required level of ionizing radiation is not well known; therefore, products are over exposed to ensure effectiveness.

***Economic Significance of Innovation*:** Radiation processing is used to sterilize $10 B of medical devices at around 200 facilities worldwide. The radiation exposure required for sterilization or decontamination has been established by exponential extrapolation of cell death from small-sample, low-level exposures. Sterility assurance levels are set significantly higher due to the uncertainty of these measurements, which places undue burden on the radiation tolerance of materials from which medical devices are made. Premium materials are used to compensate for the demands of high levels of exposure. In the case of mail decontamination, paper goods are turned brown and degraded.

***Technical Barrier to the Innovation*:** The response of biohazards to radiation at the molecular level remains to be explored. Polymerase chain reaction (PCR) has been used in forensics to verify the elimination of biohazards, e.g. decontamination of the Hart Senate office building. Methodologies used in molecular biology, i.e. marker identification and PCR, have not been adopted to facilitate the setting of appropriate radiation exposure levels to be used in industrial radiation sterilization and to verify the elimination of biohazards.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Standard methods need to be established and then conducted to determine the minimum radiation exposure needed for sterilization. The required levels for elimination of biohazards, such as anthrax, e. coli, salmonella, staphylococcus aureus, and pseudomonas, need to be established.

***Potential Solutions to Measurement Problem*:** Through use of biomarker identification and PCR techniques required levels of ionizing radiation can be established. Armed Forces Radiobiology Research Institute (AFRRI) has begun to identify the biomarkers affected by radiation. Such methods can be applied to bio-hazards, not just diseased tissue and cells. The convergence of these techniques along with the possibility of real-time PCR analyses will greatly benefit industrial radiation processing.

***Technology at Issue*:** Laser-based products – from telecommunications to homeland security applications

***Submitter*:** Marla Dowell

***Technological Innovation at Stake*:** Underpinning laser-driven innovations in fields as diverse as materials processing, medicine, communications, entertainment, and range finding is the ability to accurately characterize laser power and energy. Blue lasers, for example, represent a recent innovation in laser technology, since their short wavelength enables greater storage capacity, and as the last primary color to be tackled, pave the way for a new lighting paradigm. Blue lasers are being incorporated into high definition DVD systems, compact water purification systems, and detectors of hazardous chemical and biological agents.

***Economic Significance of Innovation*:** Laser power and energy are parameters used to characterize the performance of nearly all optoelectronic devices. Optoelectronics are at the core of systems that drive the information economy: they are the "black box" behind telecommunications, data storage systems, instrumentation and lighting. Some estimates place a value of $1 billion on blue laser products alone. In 2000, an independent economic impact assessment estimated the net benefits associate with NIST laser calibration services to be between $17.1 and $30.3 million. NIST calibration services and development result in better measurements of laser power and energy which in turn lead to better performance and reduced costs for optoelectronic devices, furthering improvements in other segments of the economy.

***Technical Barrier to the Innovation*:** The growth of the blue laser market and adoption of many laser-driven innovations is limited by the ability to accurately, reliably measure laser power and energy. These measurements are limited by the availability and cost of laser sources, detectors, and calibration services.

***Stage of Innovation Where Barrier Appears*:** R&D, Production, End Use

***Measurement-Problem Part of Technical Barrier*:** There are currently no traceable standards in the world for blue laser sources between 260 and 400 nm, or for high power tunable lasers which are used in rapid prototype products. Without such standards, accurate characterization of such optoelectronic sources and detectors is compromised and market adoption impeded.

***Potential Solutions to Measurement Problem*:** Current research on the characterization of lasers, detectors, displays, and related components could be expanded to address blue lasers and high power tunable lasers. Once standards are developed, calibrations services could be launched to address these gaps.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** Electrical and Electronics Standards Traceability

***Submitter*:** R. E. Elmquist

***Technological Innovation at Stake*:** Commercial quantum-based standards are required to provide easy-to-deliver traceability chains to the SI for all electrical units. The first electrical quantum-based standard (the Josephson volt) showed that commercialization follows a path of gradual adoption by major technology centers. This path is easily disrupted if the technology is not well supported by its developer.

***Economic Significance of Innovation*:** Electrical sensors and transducers make up a substantial part of the cost of high technology, especially in avionics, guidance, resource exploration, and medical and scientific equipment. Direct SI calibration traceability gives confidence in the test and engineering laboratory, and conveys this confidence to end-users and customers who rely on this technology. Benefits such as reduced research and engineering costs, reduced calibration costs, and increased production yields can also be achieved.

***Technical Barrier to the Innovation*:** The traditional concept of traceability includes artifact calibrations at NMI laboratories, Standard Reference Materials (SRMs), and transportable primary standards. Emphasis on recognition by accrediting organizations has improved awareness of SI traceability and generated much documentation for quality systems; however, the actual process of providing traceability remains complex and expensive for many companies. The apparent increase in complexity of quantum standards poses a barrier to commercialization and adoption.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The dissemination of the volt has advanced to the point of common use in about 20 U.S. standards laboratories of commercial quantum standards related to the Josephson volt. However, other electrical measurements such as resistance and capacitance still utilize extremely complex traceability chains to achieve reliable uncertainties. Investigation of the methods of producing, characterizing, and deploying two new quantum standards, quantum Hall resistance (QHR) and the single-electron-counting capacitance standard (ECCS), is the next challenge. Developing the staging process to deliver these SI-based standards directly to technology users requires broad expertise and superb engineering resources. From Thomas Wunsch of Sandia National Labs, "The concept of the transportable Josephson voltage standard has been an extremely useful one that we have derived significant benefit from. A similar concept, adopted for resistance measurement would possibly be of comparable value."

***Potential Solutions to Measurement Problem*:** Develop, support, and commercialize quantum standards, including the QHR standard (adoption has not progressed) and ECCS standard (under development at NIST). Lockheed-Martin purchased a QHR system in the late 1990s, but lack of trained staff forced them to retire that system. The U.S. Navy (NAVAIR command) recently purchased a commercial QHR system. This is a simpler "second-generation" system, but will require extensive staff training for effective use.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Electronic instruments including test and measurement.

***Submitter*:** Sam Benz

***Technological Innovation at Stake*:** Quantum-based voltage standards are poised to extend their accuracy from dc metrology into digital, audio, power, and rf applications. New innovations in Josephson junction materials and circuit technology are enabling quantum voltage standards with new features of programmability and precision waveform synthesis. Development of system components, primarily in cryogenic cooling and high-speed digital bitstream generators, is required to take the high-performance superconducting devices out of the research lab and into calibration systems or as stand alone system used directly by U.S. companies.

***Economic Significance of Innovation*:** Electronic instruments and energy are multi-billion dollar world-wide industries. Improved voltage standards will enable U.S. companies in these areas to develop state-of-the-art products with improved performance that will lead to business and consumer cost savings, as well as increased productivity. Well-engineered quantum-based standard devices could become turn-key instruments in routine use within U.S. companies or directly integrated into commercial high-performance instruments. For example, a quantum-based ac voltage standard would improve measurements of 60Hz ac power meters which will directly help the U.S. power industry and all U.S. consumers.

***Technical Barrier to the Innovation*:** The productivity of these companies and advances in their electronic instruments is limited by the availability of turnkey accurate voltage standard systems, namely in house, and ac and dc quantum-based Josephson voltage standards. For the highest performance, quantum voltage standards could even be integrated into new instruments or added as external, performance-enhancing optional components. Currently such dc quantum-based systems are difficult to use and inadequate for turn-key applications, and ac quantum-based systems are just being realized or are in development.

***Stage of Innovation Where Barrier Appears*:** R&D, Production; Marketing

***Measurement-Problem Part of Technical Barrier*:** Currently quantum voltage standard systems require an expert operator because the intrinsic technology is not conducive to automation. Newer quantum voltage technology is more easily automated and can also be applied to new electrical measurements of ac voltage and arbitrary waveform synthesis with unprecedented accuracy.

***Potential Solutions to Measurement Problem*:** Complete development of 10 V dc programmable Josephson standards and 1 V ac Josephson standards, implementing full system automation and focusing on turn-key operation of the systems.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Quantum Multifunction Electronic Instrumentation

***Submitter*:** Thomas E. Lipe

***Technological Innovation at Stake*:** Many organizations maintain a dc quantum voltage standard to ensure the accuracy of high-precision instrumentation; however an intrinsic ac standard is still in development. A programmable system that could supply both ac and dc voltage from a single instrument would enable such innovations as quantum-based temperature sensors for extreme environments, and new, high-performance ac digital multimeters. Beyond simply providing traceability to the ac representation of the volt, this system would provide a cost-effective ac SI volt.

***Economic Significance of Innovation*:** Just as the advent of the dc Josephson effect confirmed the accuracy of the Agilent 3458 multimeter and enabled its commercial success, an ac intrinsic standard would allow companies to market advanced instrumentation with more reliable accuracy. Additionally, as the reference for an "electric kilogram," an intrinsic ac voltage standard may facilitate the realization of an intrinsic standard for mass, which would benefit additional products and disciplines.

An affordable, multifunction (selectable ac and dc voltage) intrinsic standard, coupled with an on-board cryogenic refrigerator would represent a significant advance in electronic instrumentation, particularly at low voltage (1 V and below) where traditional scaling techniques begin to fail. Such an instrument would replace ac-dc difference metrology at these voltage levels, resulting in more accurate measurements of laboratory instruments such as voltmeters and calibrators, and less work for calibration laboratories with a significant savings in metrology costs.

***Technical Barrier to the Innovation*:** The present system exists only in prototype form, and is unsuitable for commercialization owing to its intense labor demands. Much more effort is required before this system is commercially viable. A new technique for producing Josephson devices will be required for voltages greater than 250 mV, and new scaling techniques may be required for voltages greater than 1 V.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** This standard exists in prototype form. As yet there is no confirmation that the system provides the correct output voltages as low as 2 mV, and new scaling techniques may be required to prove that the output voltage is correct. The electrical characteristics of the output transmission line at frequencies greater than 100 kHz will need to be understood before this system is commercially viable.

***Potential Solutions to Measurement Problem*:** (1) Determine critical electrical, thermal, and mechanical properties that would make a programmable ac voltage device suitable for commercial measurement applications, and (2) develop an onboard cryogenic refrigerator to provide cooling without using a liquid helium dewar.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Improved microwave remote sensing for weather forecasting and climate monitoring

***Submitter*:** David K. Walker & Amanda E. Cox

***Technological Innovation at Stake*:** Improved and more accurate microwave remote sensing instrumentation for global weather forecasting and climate monitoring. Data products derived from microwave remote sensing instruments include soil moisture, cloud liquid water path, rain rate, sea surface temperature, and snow cover. These data products provide more accurate forecasting and monitoring that would impact aviation, agriculture, energy, wildfire control, weather forecasting and many other disciplines. More accurate instruments result in less uncertainty in these data products and, thus, more accurate and reliable forecasting and climate models.

***Economic Significance of Innovation*:** Several economic impact studies show the benefit of an improved understanding of Earth and atmospheric parameters. For example, a study of the economic value of improved weather forecasts on the average U.S. household concluded that improving forecast attributes had a total national value of $1.73 billion/yr [1]. Another study concluded that the economic benefit in fuel savings to Quantas airlines of a 1% increase in forecast accuracy is $1.2 million/year (AUD) [2].

***Technical Barrier to the Innovation*:** The accuracy of current microwave remote-sensing equipment, specifically radiometers, is severely limited by the lack of rigorous standards. This deficiency makes it difficult to compare data taken by different instruments, and forces analysts to assume that data is more accurate than it may be. There are no measurement institutes that support the transfer of radiance scales to instruments at microwave frequencies, which creates a serious gap in the accuracy and reliability of data used for weather forecasting and climate monitoring world-wide.

***Stage of Innovation Where Barrier Appears*:** End Use

***Measurement-Problem Part of Technical Barrier*:** The accuracy and total uncertainty of microwave radiometers can only be determined in a rigorous fashion using a microwave brightness temperature standard target, a calibrated standard radiometer, or (more likely) a combination of the two. Methods to characterize standard targets and remote-sensing radiometers need to be developed.

***Potential Solutions to Measurement Problem*:** R&D to develop a suite of microwave brightness temperature standards covering important frequency bands in use by the remote-sensing community. A comprehensive uncertainty analysis of these standards and the sources of uncertainty within typical instrument architecture is a necessary part of this development. Uniform methods of testing and calibrating radiometers using these standards are also required.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Next generation electrical instrumentation

***Submitter*:** Yicheng Wang

***Technological Innovation at Stake*:** Emerging technologies such as integrated nano-biosensors and next-generation electrical instrumentation require new and better electrical standards for calibrations. New dissipation factor measurement capabilities for capacitance standards are needed for calibrations of nano capacitive transducers, new capacitance bridges, LCR meters, and network analyzers.

***Economic Significance of Innovation*:** Capacitive transducers are widely used in nano devices and their traceability is needed when the new devices become commercialized. New measurement capabilities of dissipation factor of capacitors will also enable traceability of energy and power instruments needed under the new rules for international trade, and better characterization of dielectric materials, aged underground power cables, and high-temperature superconducting cables. Precision capacitors are also essential in a variety of electrical instruments including capacitance bridges, LCR meters, lock-in amplifiers, and network analyzers. These electrical instruments, in turn, have wide applications in a broad market; for example, maintenance of aircraft for reliability, quality control in integrated circuits production, DNA characterization, and real-time monitoring of wireless communication networks.

***Technical Barrier to the Innovation*:** There are no dissipation factor measurement services available in the U.S., so domestic instrument manufacturers have to turn to overseas which do not completely address their needs. For example, Andeen-Hagerling, Inc. in Ohio, which is the manufacturer of the world's most accurate commercial capacitance bridges, has relied on a foreign national lab for dissipation factor calibrations in the past. However, the solution has become unsatisfactory to Andeen-Hagerling because the calibration uncertainties now significantly exceed the resolution and stability of their new instruments.

***Stage of Innovation Where Barrier Appears*:** R&D, Production, Marketing, End Use.

***Measurement-Problem Part of Technical Barrier*:** Accurate calibrations of dissipation factors require reference capacitance standards whose capacitance and dissipation factor can be calculated from basic electromagnetic theories and a scaling system that allows direct comparison between the reference standards and transportable customer standards from 1 pF to 1 μF in the frequency range from a few Hz to 1 MHz.

***Potential Solutions to Measurement Problem*:** R&D to improve and characterize toroidal cross capacitors whose dissipation factor can be calculated, and to develop automated capacitance and dissipation factor scaling bridges for dissemination. Characterized transportable standards that can be utilized in an industrial environment. An in-depth uncertainty analysis to identify individual measurement contributions to overall uncertainty budget.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Commercial realization of high-end multijunction thermal converters to enable high performance electronic instrumentation

***Submitter*:** Thomas E. Lipe

***Technological Innovation at Stake*:** High performance equipment relies on rigorous standards and testing to ensure it operates within specified parameters. Presently the most accurate measurements of ac voltage and current are made by comparing the heating effect of an unknown ac signal to that of a known dc signal using a device known as a thermal convert. The most accurate thermal converters are multijunction thermal converters (MJTCs). These high-end measurement devices are difficult to manufacture and operate, requiring a laboratory environment to ensure accurate results. Indeed, practically all MJTCs are used at National Metrology Institutes.

***Economic Significance of Innovation*:** If MJTCs could be made robust and easily manufactured, while maintaining their inherently high degree of accuracy, they could be directly integrated into critical test and measurement equipment. Such devices could be deployed in equipment which is difficult to service, such as military field equipment, or where reliability and accuracy is critical, such as test equipment for applications in avionics, medicine, and transportation. In addition, these devices may be easily designed as high-performance vacuum gauges, flow meters, and infrared sensors. The savings in cost to the end user is expected to be dramatic, not only in initial cost (perhaps $20 for an MJTC instead of $200 for a traditional, hand-built device), but also in the increased reliability (fewer spares required) and accuracy (enables market penetration for an instrument equipped with MJTCs.)

***Technical Barrier to the Innovation*:** Although small quantities of these devices have been successfully fabricated for research, successful fabrication of commercial quantities of MJTCs has not been demonstrated. It is possible that larger, commercial quantities cannot be successfully fabricated using presently available techniques. In addition, the most appropriate MJTC for instrumentation exists only as a prototype, and more work is required to prove its efficacy in a commercial environment.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Any device intended for use in a commercial instrument must be proven to meet the requirements of that application. Intensive measurements and modeling of thermal and electrical properties of these devices must be made before full development and implementation can occur.

***Potential Solutions to Measurement Problem*:** Determine critical electrical, thermal, and mechanical properties that would make these devices suitable for inclusion into a mass production semiconductor fabrication process and thereafter into high-performance instrumentation.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Synthetic Laser Interferometry

***Submitter*:** S. D. Phillips

***Technological Innovation at Stake*:** Exploiting recent advances in optoelectronics, manufacturers of large scale (10 m – 100 m) optical metrology instrumentation are developing a new generation of laser scanning systems that are potentially capable of measuring objects one to two orders of magnitude faster than conventional interferometric techniques.

***Economic Significance of Innovation*:** Improvements in the accuracy of synthetic laser interferometry significantly increase the number and complexity of the applications of this technology. Absolute distance measurements using synthetic interferometry reduce measurement time by at least an order of magnitude over conventional interferometry by removing the requirement for the unbroken beam paths that are so difficult to generate and maintain. The use of this class of measurement technology impacts many sectors of the economy by significantly reducing the time to manufacture and assemble large components, as well as the time to repair and/or upgrade large mechanical systems such as aircraft components, petrochemical refinery tank and piping layouts, and power plants. Additionally, such systems can eliminate many worker safety issues, e.g. heights, from the measurement process.

***Technical Barrier to the Innovation*:** Variability in performance of the optoelectronic components used in synthetic laser interferometry is creating a technical barrier to its performance potential. Optoelectronics are susceptible to a variety of difficulties arising from non-ideal electronic components, parasitic capacitance, thermally induced electronic drift, limited phase discrimination, and other effects that result in behavior not predicted by first principle calculations.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Experimental measurements are required to identify and quantify the factors causing performance variability, allowing for modifications for product improvement, and to verify the accuracy of the systems. The most direct route to, and the ultimate arbitrator of, measurement accuracy for these large scale dimensional metrology systems is a direct comparison to a high accuracy realization of the SI meter.

***Potential Solutions to Measurement Problem*:** The generation of length standards over the large distances applicable to these systems requires special facilities, instrumentation, and metrological skill. Development of a high accuracy calibration facility could provide these.

Case Study – Measurement Needs

***Technology at Issue*:** Micro-Feature Metrology

***Submitter*:** S.D. Phillips

***Technological Innovation at Stake*:** Machined micro-features (e.g. 100 μm feature size) represent a rapidly expanding array of products produced by such techniques as micro-machines and LIGA (German acronym of lithography, electroforming, and molding). Small features are increasingly designed into optical lenses, optical fibers and their connectors, DNA processing chips, drug delivery systems, and a myriad of other applications. However, the fact that the quality of these microfeatures is imprecisely known is limiting both their widespread use and potential improvement.

***Economic Significance of Innovation*:** Micro-features are associated with high value added components with significant economic leverage in the economy. For example, fuel injectors with holes as small as 60 micrometers in diameter would benefit from precision measurement so as to standardize dimensions, thus increasing fuel economy and reducing pollution; even a 0.4% increase in fuel efficiency would represent $1 B annual savings to the U.S. As another example, the $3 B telecom connector market would benefit from the ability to measure the geometry of fiber ferrules or similar fiber alignment devices used in optical switches. Sub-micron alignment is needed to minimize connection losses, and consequently very small measurement uncertainties are desirable. More generally, whereas the $1 B American MEMS industry currently relies on image-based measurements at modest accuracy, we can expect that a maturing MEMS industry will face the same needs for progressive precision as seen in manufactured products on a larger scale, namely high accuracy reference measurements to secure and improve the traceability chain.

***Technical Barrier to the Innovation*:** These components are too delicate to inspect and measure with conventional contact probing techniques. Additionally, such small probe styli are extremely fragile and conventional probing technology destroys them during the measurement process. These microfeatures cannot be validated or improved if they cannot be measured.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Currently there is no available measuring technology which is small enough to assess microfeatures, robust enough for use in these measurements, and of high enough accuracy to meet industry needs.

***Potential Solutions to Measurement Problem*:** Develop coordinate measurement probing technologies that are capable of 3D coordinate metrology of internal features of 100 μm size with an uncertainty of 0.1 μm or less. Develop calibrated reference artifacts for use by high accuracy metrology companies in development of this instrumentation.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Aspheric Optics

***Submitter*:** Ulf Griesmann /Robert Polvani /Steve Phillips

***Technological Innovation at Stake*:** Precision surfaces with shape fidelity to 1nm or better enable advanced optical instrumentation in many industries, research, and defense, and in many non-optical applications, e.g. in the semiconductor industry. The application of aspheric optics is critical to designing and commercializing new consumer and military optical products such as semiconductor fabrication, remote sensing, compact imaging systems, optics for medical applications, and CD/DVD recorders-players.

***Economic Significance of Innovation*:** Contemporary optical design is shifting from spherical based optical elements toward aspheric optics. Advanced optics is a pervasive enabling technology which is key to new consumer, bio-medical, and military products, especially ones which can compete successfully in a globalized economy. Designers and fabricators of precision optics rely on optics with complex surface shapes (aspheric or free-form surfaces) to improve performance, use fewer elements, cut weight, and lower cost. In many fields, optics and optical systems incorporating aspheric optics play the role of an enabling technology which offers a significant competitive advantage and are likely to displace their conventional counterparts. Both the economic and national security health of the nation depend on a robust domestic optical industry.

***Technical Barrier to the Innovation*:** Production of aspheric optics is hindered by inefficient optical testing methods. Some existing methods meet only immediate and specific uses. For high volume production optics, device build-up is used to test for function, not to test to design specifications of individual optical elements. Hence efficient optimization of manufacturing is impeded.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** No single, widely recognized, general, validated way exists for calibrating or measuring complex surfaces with uncertainties at the nm-level. The accepted techniques include profilometry and coordinate measuring machine metrology in cases where moderate uncertainty levels are sufficient. More commonly, general interferometry using “null optics”, either refractive or computer generated holograms (CGH), are used or sub-aperture “stitching” interferometry. Implementing any of these methods is expensive and all represent a high barrier to using aspheric optics in advanced optical designs.

***Potential Solutions to Measurement Problem*:** The development of an entirely new means of asphere calibration is needed that will allow rapid, accurate, and inexpensive measurements. Candidates for calibration method include curvature-based and functionality-based methods.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Coordinate Metrology Data Analysis

***Submitter*:** Craig Shakarji / S.D. Phillips

***Technological Innovation at Stake*:** Validated coordinate metrology data analysis software would be of great value to the discrete parts manufacturing sector. Manufacturers of coordinate metrology data analysis software seek the ability to analyze data using a variety of mathematical fitting algorithms. However, only one type of algorithm, least squares, can currently be tested for its accuracy by an NMI calibration. Other algorithms are unverified and some are known to have large systematic errors. Furthermore, even with least squares fitting, NMI calibrations exist only for a handful of common shapes, leaving the field of complex surface fitting largely untested.

***Economic Significance of Innovation*:** The coordinate metrology software industry is relatively small (estimated at $20M/year). Yet this analysis capability is crucial to the much larger industry of discrete mechanical component manufacturing, where coordinate measuring machines are widely used to verify dimensions of parts produced. Increased reliance on validated algorithms in coordinate measuring machines translates to greater confidence in the dimensions of parts produced, with potential savings in machining costs as measurement uncertainty uses a smaller portion of part tolerances, scrap is reduced, and less re-measuring is done. While these are small savings individually, when repeated on part after part through out the multi-billion dollar discrete parts manufacturing industry, the impact adds up.

***Technical Barrier to the Innovation*:** Reference algorithms, designed to validate the performance of coordinate metrology data analysis software do not exist, except for the case of least squares fitting of simple shapes. There are currently no ways to establish the validity of non-least squares fitting algorithms or even least squares fitting algorithms of complex surfaces.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Currently, there are no testing facilities available for either non-least squares fitting algorithms or least-squares fitting of complex surfaces. Specific metrics need to be developed, and agreed upon by the industrial community, that characterized the performance of an algorithm--a task that is complicated by both the complex and nonlinear nature of these fitting procedures.

***Potential Solutions to Measurement Problem*:** Development of a high accuracy reference algorithms and performance metrics for algorithm testing.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Magnetic Data Storage

***Submitter*:** T.V. Vorburger/S.D. Phillips

***Technological Innovation at Stake*:** The technology at stake is the continued miniaturization of recording density in the magnetic data storage industry, which relies on the ability to manufacture smaller head structures with improved surface quality.

***Economic Significance of Innovation*:** Smaller head features with improved surface quality improve the performance of existing products and can yield new, innovative products that are otherwise not possible. Magnetic data storage devices comprise one of the innovation drivers of the successful and hugely important $200B microelectronics industry.

***Technical Barrier to the Innovation*:** Decreasing the spacing between the magnetic head and the disk medium depends on decreasing the trailing edge pole tip recession (PTR) of the slider head as one of the key factors. However, as the head-medium spacing decreases from 20 nm in 2003 to a projected 2.8 nm in 2013, industry will not be able to make the step height measurements to the required accuracy.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Industry has called on NIST to provide calibrations for its height measurements with an accuracy of 10 pm in order to satisfy their specifications for pole tip recession in the near future. Industry cited as its second highest priority in the head disk interface area the development of a physical artifact to verify and standardize performance of AFM and optical equipment for measuring Angstrom level pole tip recession, with a measurement target of 100 pm with associated measurement accuracy of $\pm$ 10 pm by 2007.

***Potential Solutions to Measurement Problem*:** In the short term, a solution is the Si (111) single atom step height standards (312 pm) calibrated by NIST with an established measurement procedure for the user to follow. In the long term, adaptation of such standards to geometries closer to that of a pole tip structure and development of Si (100) standards with heights of about 100 pm would address the measurement need.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** Areal Measurement of Surface Texture

***Submitter*:** Theodore Vorburger and S.D. Phillips

***Technological Innovation at Stake*:** The technology at stake is enhanced accuracy measurement instrumentation to perform areal (3D) measurements of surface texture. While this instrumentation is used in a wide array of metal working industries, including automotive, aerospace and heavy equipment, as well as the micro-optics area, its accuracy must be verified and improved.

***Economic Significance of Innovation*:** Increasing world competition in manufacturing drives increased productivity in U.S. manufacturing which in turn drives improved speed and accuracy in the metrologies required to verify that the surface texture of components are manufactured to specifications. While the surface texture instrumentation is only about a $25M market, it services the automotive, aerospace, and heavy equipment industries by providing 3D characterization of surface texture of components for products totaling more than $350B in value. This kind of surface characterization is more complete than that provided by 2D stylus profiling instruments and enables more extensive analysis of surface quality and the development of more refined surface specifications that help industry reduce the warranty costs on their manufactured products.

***Technical Barrier to the Innovation*:** Interferometric microscopy for measurement of surface texture is an important metrological development where the U.S. is the world leader. These tools enable fast areal surface texture measurements to be made, thus improving the speed of surface metrology in manufacturing. However, the accuracy of these measuring tools needs to be improved and verified by at least a factor of ten in the 50 nm to 300 nm range of roughness so that users can be confident that their roughness measurement results are accurate to 5%.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** NIST recently discovered a bias in white light microscopy measurements of roughness, spanning multiple instrument manufacturers, which can be as large as 50% of the measured roughness average value at the 100 nm level. The root cause of this error is not yet understood, but needs to be determined and corrected before a large number of measurements to verify compliance to roughness specifications are thrown into doubt.

***Potential Solutions to Measurement Problem*:** Develop a model for white-light interferometry that successfully predicts the direction and size of the measured biases and potentially minimizes or corrects the problem.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue**:** Hyperspectral Imaging

Submitter**:** Gerald T. Fraser

Technological Innovation at Stake**:** Multispectral remote sensors produce images with only a few wavelength bands, but hyperspectral remote sensors can collect image data in dozens or hundreds of spectral bands. Hyperspectral imaging systems will replace conventional photographic, multispectral, and infrared imaging systems, providing more detailed reliable chemical and physical data about the target.

Economic Significance of Innovation**:** The applications for hyperspectral imaging are broad: in chemical and biological agent detection, climate research, astronomy, medicine, process monitoring, environmental remediation, disaster prevention, fire rescue, and defense (reconnaissance, surveillance, and targeting). One of the most important uses for hyperspectral imaging can be used not only to distinguish different categories of land cover, but also the defining components of each land cover category, such as minerals, new sources of oil and soil and vegetation type.

Technical Barrier to the Innovation**:** The sensitivity and the stray-light rejection of the hyperspectral imaging systems are not advanced enough for broad acceptance. The light from the image is divided spatially and then within those spatial windows is spectrally divided. The resulting light to be detected is extremely small. Any stray-light within the system will overwhelm the detectors compared to the desired signal. Additionally, data processing and analysis remains a challenge—huge amounts of data are possible and insufficient data standards and optical properties databases do not exist.

Stage of Innovation Where Barrier Appears**:** R&D

Measurement-Problem Part of Technical Barrier**:** To obtain accurate chemical and physical information from a scene or target requires that each pixel of the image be calibrated spatially and spectrally. For spectral calibration, both the wavelength scale and intensity scale (radiance) must be accurately known. In addition, methods must be developed to optimize these systems to eliminate stray-light and compensate for stray-light that cannot be eliminated.

Potential Solutions to Measurement Problem**:** Simultaneous spectral and spatial scene generation technology promises the ability to artificially create realistic optical signatures from scenes based on either high-end measurements or radiative-transfer theory to quickly and inexpensively calibrate hyperspectral imagers.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Solid State Lighting

***Submitter*:** Cameron Miller, Wendy Davis, and Yoshi Ohno

***Technological Innovation at Stake*:** The use of visible light emitting diodes (LEDs) for general lighting, solid state lighting (SSL), provides significant improvement in energy efficiency and versatility over current technologies. The technology started with combustion, moved to incandescence or heated filaments, and currently uses discharge lamps.

***Economic Significance of Innovation*:** According to the Department of Energy (DOE), lighting accounts for 8% of all energy consumption in the United States and 22% of electricity nationwide. If SSL replaced all existing lights, the DOE estimates customer savings of $115 billion by 2025 and a 10% reduction in green-house emission gases. Additionally, 40% of lumen market is turned over annually, so any acceleration of technology will be implemented quickly and will yield large economic impacts.

***Technical Barrier to the Innovation*:** Accurate assessment of color rendering is critical, not only because color rendering is a major determinant of customer satisfaction with lamps, but also because color rendering has a trade-off relationship with luminous efficacy. Color Rendering Index (CRI) is a metric that attempts to quantify the extent to which a light source allows for accurate color perception of illuminated objects. The existing CRI is flawed and particularly ill-suited to the emission properties of LEDs.

***Stage of Innovation Where Barrier Appears*:** Marketplace

***Measurement-Problem Part of Technical Barrier*:** A complete set of vision science data dealing with the effects luminous intensity, chromaticity and spectral power distribution does not exist and is required to construct a new CRI. Such data are required to establish the validity and reliability of any proposed new metric.

***Potential Solutions to Measurement Problem*:** The development of a state of the art vision science facility that is spectrally and intensity tunable will allow the development and standardization of a new color rendering metric that more accurately represents the response of the human visual system through a combination of computational analysis, simulations and vision experiments.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Surface Appearance Instrumentation

***Submitter*:** Maria Nadal

***Technological Innovation at Stake*:** The development of instrumentation to absolutely quantify surface appearance or to quantify the degree to which materials or objects match based on surface appearance is challenged by the interplay between visual perception, color, lighting, material optical properties, and surface texture. Cosmetics, coatings, clothing, food, automobiles, and appliances are some of the products for which proper management of color and appearance by manufacturers and suppliers is critical for commercial success. Currently comparisons of materials are done visually in a controlled lighting environment.

***Economic Significance of Innovation*:** Color and appearance guides nearly all consumer product purchases, often being the first attribute noticed in a store display or advertisement. Appearance matching is critical for successful manufacturing, particularly in a global economy where components of a product are manufactured at different sites for later assembly at a single site. Using the current methods of visual inspection, rejection rates of the final products are on the order of fifty percent. Better color measurement and detection can significantly reduce rejection rates (by up to 50% in certain industries) due to off-spec color.

***Technical Barrier to the Innovation*:** Color and appearance is a complex multidisciplinary phenomenon involving optical scattering, surface micro and macro structure, material optical properties, and lighting. Theory to incorporate the multidisciplinary phenomenon and visual perception does not exist.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The development of the theory between appearance and visual perception requires high-resolution measurements of surface scattering as a function of illumination, scattering angles and spatial position. High-resolution equipment and time efficient methods to collect the data are required.

***Potential Solutions to Measurement Problem*:** Development of high-resolution instruments for complete characterization of surface scattering and the determination of an optimal set of measurements (spatial, spectral, and angular) necessary to capture, specify, and render surface color and appearance including texture.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Solid State Flashing Sources

***Submitter*:** Cameron Miller, Wendy Davis

***Technological Innovation at Stake*:** The use of visible light emitting diodes (LEDs) for flashing light sources provides significant improvements over existing technology. The existing technology offers two options: rotating beacons or xenon strobes which have limited flash profiles. LED flashing light sources allow the flash profile to be optimized to greater visibility than is otherwise possible.

***Economic Significance of Innovation*:** Many flashing light initializations require electrical sources such as diesel powered generators or physical lines from electrical grids. Applications include roadway and aviation industries however the earliest user of this technology will be maritime navigation. Maritime buoys require battery storage that requires on going maintenance. By using solid state technology, the electrical source will be solar charged batteries that require little maintenance and can be implemented in hard to reach locations. This can enable more efficient and safer maritime navigation through light sources that could be cheaper to implement.

***Technical Barrier to the Innovation*:** Effective intensity is a metric that attempts to compare flashing light sources with different flash profiles. The existing effective intensity metric is flawed and particularly ill-suited to the possible flash profiles with LED flashing lights. Potential LED flash profiles cause the effective intensity to double with half the energy, which is not a real effect. Many current federal regulations use the flawed effective intensity metric.

***Stage of Innovation Where Barrier Appears*:** Marketplace

***Measurement-Problem Part of Technical Barrier*:** A complete set of vision science data dealing with the effects of flash profiles, chromaticity and spectral power distribution do not exist and are required to construct a new effective intensity model. Such data is required to establish the validity and reliability of any proposed new metric.

***Potential Solutions to Measurement Problem*:** Develop and standardize a new effective metric through a combination of computational analysis, simulations, and vision experiments that more accurately represents the response of the human visual system.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Full Corner Retroreflectors for Transportation Safety

***Submitter*:** Cameron Miller

***Technological Innovation at Stake*:** Retroreflectors are used in transportation under nighttime conditions to return light from a source to an observer that is close to the source, independent of the direction that the light contacts the retroreflector. A new technology, full corner retroreflectors, doubles the efficiency of current retroreflectors.

***Economic Significance of Innovation*:** With advances in headlight technology, the amount of light on the road is always increasing; however the light that goes above the horizon where signs are placed is significantly reduced. Without more efficient retroreflective signage, the Department of Transportation will be required to light signs which have high initialization and maintenance costs.

***Technical Barrier to the Innovation*:** Current regulations for daytime qualification specify a minimum reflectance factor under the conditions of illuminating the retroreflector at an angle of 45 degrees with respect to the surface and viewing the retroreflector perpendicular to its surface. Due to the retroreflecting properties of the device the illumination hitting at 45 degrees leaves at 45 degrees; therefore the reflectance factor is small and does not meet the minimum daytime qualification.

***Stage of Innovation Where Barrier Appears*:** Marketplace

***Measurement-Problem Part of Technical Barrier*:** Vision standards such as the candela are based on vision science experiments at light levels near detection. A complete set of vision science data dealing with the effects of luminance at higher or suprathreshold levels do not exist and are required to construct a more effective measurement method to be used to update regulations. Such data are required to establish the validity and reliability of any proposed new metric.

***Potential Solutions to Measurement Problem*:** Develop and standardize a new method for qualifying these materials based on a combination of computational analysis, simulations, and vision experiments that more accurately represent the response of the human visual system at higher levels of luminance.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Large Area LED Displays

***Submitter*:** Kevin Dowling and Cameron Miller

***Technological Innovation at Stake*:** Large area Light Emitting Diode (LED) displays are significantly brighter, more durable, viewable from a larger angle range, and more energy efficient than current self illuminated display technologies. Large area LED displays will find many applications including road signaling, billboard advertising, and stadium displays.

***Economic Significance of Innovation*:** The value of worldwide shipments of electronic displays has reach $85B in 2005, and will grow at an average annual rate of 10.6% to reach $141B by 2010. Flat panel displays account for 67% of the value in 2005 and will have 85% of the total display value by 2010. LCDs, presently the primary competitor to the CRT, grew at a rate of 17.5% in 2005 to reach a worldwide shipment value of $48B. LED displays have superior qualities to LCD technology and will become the primary device of choice in the future.

***Technical Barrier to the Innovation*:** A technical barrier to the market acceptance of large area LED displays is the characterization of the light output. Large area LED displays utilize discrete devices; therefore, they have pixilation, non-uniform emission in terms of the emitting area. When the devices are measured at different angles and distances, large fluctuations result causing inconsistency in the specification of these displays.

***Stage of Innovation Where Barrier Appears*:** Marketplace

***Measurement-Problem Part of Technical Barrier*:** The measurement-problem is that no satisfactory equivalent definition of luminance applies to both near-field and far-field viewing conditions. Luminance is defined for uniform extended sources. Since large area LED displays are made of discrete devices, pixilation occurs. The emitting area has bright and dark spots. Luminance is also defined to follow the inverse square law, such that the intensity decreases by a factor of four as the distance is doubled. LEDs are beam devices and thus do not follow the inverse square law.

***Potential Solutions to Measurement Problem*:** A solution is to determine the effect of non-uniform emitting area on the human perception of luminance. Correction factors can be developed based on the bright-dark fluctuation. These correction factors would be part of a working definition for luminance that would take into account the beamed aspect of the LED devices.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Small Force Metrology

***Submitter*:** Jon Pratt and Kevin Jurrens

***Technological Innovation at Stake*:** The development of calibrated ultra small-scale force measuring systems is the *Technological Innovation at Stake*. Currently, scientists and engineers lack traceable means to verify the performance of ultra small-scale force measurement systems, such as instrumented indentation machines (IIM) and atomic force microscopes (AFM). These instruments are vital tools to a number of manufacturers, and are routinely used to measure everything from the adhesion of paint, to hardness of material coatings, to inter-atomic forces.

***Economic Significance of Innovation*:** AFMs and IIMs have become indispensable to users who are routinely tasked with verifying the mechanical performance of micro and even nanoscale devices and nanostructured materials during the development stage of fabrication processes. The ability to measure small forces accurately will enable the provision of essential infrastructure for important advances in such diverse and high impact areas as: (1) ultra-thin coatings critical to the information storage capacity of computer hard disk drives, the durability of turbine blades, and the performance of paint on automobiles; (2) nanomaterials development and applications; and (3) nanomanufactured mechanical devices. The global demand for nanoscale materials, tools and devices, for example, is estimated to reach as high as $1 trillion during the next decade.

***Technical Barrier to the Innovation*:** Current small-scale measuring systems are reliably accurate in dimensional metrology only. Without adequate calibration, they cannot accurately produce measurements of force. Industry's use of scanning probe microscopes to characterize the performance of nano- and molecular-scale components exceeds USMS current capabilities for small force measurement by more than three orders of magnitude. Thus, they are currently limited to use in a qualitative mode for force-related aspects of nanomechanical performance.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** There is an acute need for easily transported small force standards with which to calibrate instruments like the AFM and IIM as these instruments are increasingly employed in nanomechanical test and measurement systems for product and process development across a wide range of industries.

***Potential Solutions to Measurement Problem*:** The development transportable small force standards for use in calibrating AFMs and IIMs will first require accurate characterization of atomic and molecular forces. Then suitable intrinsic standards will have to be identified, tested, and developed for the dissemination of this new capability.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** SI Torque Metrology

***Submitter*:** Rick Seifarth

***Technological Innovation at Stake*:** There is industrial need to be SI traceable to a US national standard for torque or to have access to a national torque value verification standard. Current users of torque and torque-related metrology in the U.S. rely upon the combination of individual torque component measurements from NIST and/or other laboratories in order to derive torque values that approach those which could be considered to be standard values.

***Economic Significance of Innovation*:** Torque measurements are used heavily during assembly processes and testing throughout the aerospace, automotive and manufacturing sectors. Uncertainty evaluations surrounding the measurements are based upon current best efforts by private and independent bodies. The lack of a singular national torque standards laboratory requires time-consuming and costly maneuvers by each of multiple individual users throughout the supply chain in order to justify their own systems to even a basic level of uncertainty acceptance by other users. For example recalling a single jet engine due to any problem including poor assembly of torqued components can trigger costs to the manufacturer that begin at $500,000. The costs, of course, can be far higher when improper torque values are not identified and component failure occurs.

***Technical Barrier to the Innovation*:** Large uncertainties associated with current techniques and transducers are due to lack of control over the physical component variables in the primary torque standards and the subsequent difficulty of dissemination of torque values through transfer calibrations. The traceability chain needs to be shortened and/or uncertainties propagating through it need to be lowered.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Currently, successful characterizations of the individual components that combine to form the derived torque standard value are not feasible. These components include applied force, or measurements of mass, gravity and air buoyancy; length of moment arm; and an assessment of misalignments inherent and relevant to each physical setup. Yet such characterizations are essential for valid traceability of the torque measurement with acceptably low uncertainties using the current modes of torque transfer.

***Potential Solutions to Measurement Problem*:** Design, manufacture, and test a primary torque standard and an associated secondary torque transducer as a proof of concept. In addition to provision of accurate measurements of torque, the system must display adequate stability and ruggedness to impart credibility to the process.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Time-invariant Kilogram Realization

***Submitter*:** Vincent Lee, Zeina Jabbour

***Technological Innovation at Stake*:** There is a need for a new technological approach to lay the foundation for a time-invariant realization of the Kilogram. Currently, the mass standard is defined in ambient air. As such, its mass is subject to change over time: a gain due to absorption or adsorption of contaminants in the surrounding air, and a loss due to material wear as a result of handling during usage. Its stability has been about 50 micrograms over the last 100 years; however, the relative precision of commercially-available mass comparators is about 1×10^{-10}. The progress in the development of a stable definition of mass has been limited by the inherent instability of existing mass artifacts and a lack of fixed environments. Also, because the Kilogram is artifact based, it is also the weakest link that affects the robustness of the SI.

***Economic Significance of Innovation*:** The creation of a time-invariant realization of the Kilogram will result in an exceptional efficiency in the dissemination of mass, an increased accuracy in mass measurements, a reduced frequency of the calibration of mass artifacts, the elimination of major quality assurance procedures, and a savings of hundreds of thousands of dollars in cost per NMI and millions of dollars by state and local governments and industry. For the pharmaceutical industry, this is an important issue in the design and manufacture of medicines, and for the nuclear industry, it is important for the accountability of nuclear materials with respect to homeland security. Given the current standard's inherent instability over time and constant vulnerability to damage or destruction, it cannot be depended upon as an unchanging, repeatable standard – as if it were an indisputable fact of nature.

***Technical Barrier to the Innovation*:** Currently, all mass standards are defined and measured in air, and they are not physically stable over time. To achieve temporal stability of the mass artifact, it must not be exposed to air. Thus a new measurement method is required. In order to be effective, this new measurement method must be able to attain at least the current uncertainties used by the mass metrology community. In order to be a practical tool in the dissemination of the Kilogram standard, it will also need to be developed beyond the prototype stage.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Since conventional measurement of mass standards is affected by the surrounding ambient air, working toward time-invariant realization of the Kilogram will require switching to a vacuum environment. The development of mass calibration methodologies and equipment compatible with a vacuum environment will be required.

***Potential Solutions to Measurement Problem*:** NIST is currently working on a project to lay the foundation for the development of a new realization of the Kilogram. Eventually mass comparator companies could develop equipment for secondary dissemination.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Highly Focused Ultrasound Medical Devices

***Submitter*:** Don Eitzen

***Technological Innovation at Stake*:** Within the well-established ultrasonic medical devices industry is a fledgling subfield of Highly Focused Ultrasound (HIFU)-based devices. While showing great potential, only a few limited applications have been approved by the U.S. Food and Drug Administration. This is due, at least in part, to safety concerns related to incomplete characterization of the performance of such devices. Innovative devices for potential use in areas such as battlefield wound cauterization, tumor destruction, and heart ablation are not yet in the marketplace due to inadequate metrology support for their performance characterization.

***Economic Significance of Innovation*:** There are about 12,000 ultrasonic device manufacturers, with about 10,000 devices submitted to the FDA for approval each year. Overall, the size of the industry in 2002 was $4.7 billion. Getting these new devices to market would not only expand the size of the market, but would also reduce the need for more costly medical treatments in some cases. For example, it would be less expensive to have heart ablation performed by a non-invasive HIFU-based procedure versus the current surgery that involves direct, open access to the heart and a lengthy, costly recovery period.

***Technical Barrier to the Innovation*:** Device performance characterization is not sufficient for acceptance of this technology in safety critical medical applications.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Adequate characterization of the performance of these devices requires a complex set of measurements taking into account multiple parameters of the system, as well as the complex properties of both the propagating and target materials. One cannot simply measure average device performance, as this doesn't capture energy peak variations over either space or time.

***Potential Solutions to Measurement Problem*:** To effectively characterize these devices, modeling, based on first principles, incorporating all the parameters of the device, the intervening material (soft tissue, organs, bone) and the intended target material, should be performed. Based on this modeling, series of experiments could be designed and implemented to measure the point field quantities and validate the safety of the performance of the device.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Infrasonic Metrology

***Submitter*:** Victor Nedzelnitsky and Randall P. Wagner

***Technological Innovation at Stake*:** The development of calibrated, SI-traceable, easily transported transfer standards for providing acoustical measurements in the infrasonic range – below the typical lower frequency limit of human hearing (20 Hz), with overlap capability to the low audible frequency range. This R & D involves the confluence of: promising new technologies in sensor element and adaptive array design, recent developments in signal processing, event analysis, characterization, localization, databases, computational models, and analyses of infrasound generation and wave propagation mechanisms. Objects of this R & D include infrasound from natural phenomena such as hurricanes, tornadoes, landslides, earthquakes, tsunamis, volcanic activity, ocean swells, and meteors.

***Economic Significance of Innovation*:** Currently there is no SI-traceable method at these frequencies for providing the acoustical measurements needed to realize the potential of current and proposed R & D that aims to study, detect, identify, locate, and, when appropriate, warn of many natural phenomena and man-made events. Man-made events such as rocket launches, airbag deployment, supersonic aircraft travel, and explosions resulting from nuclear and conventional weapons tests also generate infrasound, and can have enormous economic or national security impact. A single natural disaster can cause many deaths and cost many billions of dollars, much of which could be averted through improved prediction, detection, and early warning capabilities.

***Technical Barrier to the Innovation*:** The transfer standards must be applicable to the secondary calibrations of the various different sensors in monitoring systems designed for different natural phenomena and different man-made events. It is not known which of the available candidate standards are suitably stable, robust, and can be calibrated with the proper uncertainties and traceability. Nor is it known which candidates are appropriate for secondary calibrations of particular sensors. Modifications or new designs of standards may be needed if none of the available candidates can meet the requirements.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Selection of candidate device(s), development and validation of calibration methodologies for device(s), and ongoing calibration support of device(s).

***Potential Solutions to Measurement Problem*:** NIST could identify, validate, and provide SI-traceable calibrations of suitable transfer standards from commercial suppliers of potentially suitable candidate transducers. NIST, U.S. Dept. of Energy (DoE) laboratories, industry, and researchers could cooperate to develop suitable secondary procedures for use of the calibrated transfer standards.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Robust Thermometers for Next Generation Power Plants

***Submitter*:** W. Tew, D. Ripple

Technological Innovation at Stake: Next generation nuclear power electricity generation plant designs incorporate a gas-cooled helium reactor with a high efficiency gas turbine to achieve plant design efficiencies approaching 50%. Design operating temperatures range between 800° C and 900° C for the primary heat transfer medium, helium gas. At-temperature thermometer lifetimes are anticipated to be in the 6 to 10 year range, with accuracy requirements, primarily drift in response over several years, of better than 1%. This includes over-temperature capability requirements that may range to well above 1200° C. These are challenging requirements for which numerous tests of existing thermometry technologies have demonstrated failure. New temperature approaches are needed to provide plant control systems with the information necessary to achieve safe and effective operation.

***Economic Significance of Innovation*:** Successful expansion of U.S. electrical generating capacity based on next generation nuclear technology coupled with advanced gas turbine approaches have the advantage of lower long-term operation costs, fuel obtained domestically, high capacity, and long operating lifetimes. As the price of imported natural gas rises, nuclear plant-based electricity generation: achieves costs below those of gas-fired plants; has much longer operating lifetimes and lower operating costs; does not depend upon imports; and does not emit greenhouse gases. Advanced process control technologies are an important part of such a deployment strategy.

Technical Barrier to the Innovation: The failure of present thermometry technologies in high temperature, long-term testing is due to degradation of the materials composing the probe itself, the hot part. In most resistance, or thermocouple thermometry, materials degradation is manifest by large and unpredictable changes in the thermometer response that negates any prior calibration. Deployment of next generation nuclear electrical generation technology will depend upon many factors, however effective control of these plants is essential and a number of process measurement barriers, reliable thermometry being one, must be overcome to achieve such deployment.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Operating requirements ranging from 800° C and 900° C with excursions to above 1200° C, pose significant probe materials stability issues and require new signal processing approaches insensitive to inexplicable changes in thermal coefficients of the materials. Advances in two measurement science and technology areas are needed, (1) development of thermometry probes capable of withstanding the 800° C and 900° C normal operating range tolerant of temperature excursions, and (2) development of probe response measurement approaches of sufficient accuracy and stability that do not directly depend upon predictable thermally induces resistance change.

***Potential Solutions to Measurement Problem*:** Candidate probe materials choices are limited to high temperature ceramics and the refractory metals, melting temperatures above 1900° C. Of the temperature measurement technology choices available, Johnson Noise Thermometry (JNT), has the significant advantage of being (1) insensitive to drift in probe resistance value and (2) a fundamental thermometry method that does not require calibration. To successfully realize the use of JNT for this application requires significant measurement science research to form the basis for improvements to probe design and operation and, perhaps more importantly, to the development of robust signal processing approaches.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Dissemination of Temperature Standards

***Submitter*:** Dean Ripple

***Technological Innovation at Stake*:** Innovations in thermometry technologies and methods may be required to meet increased performance requirements based upon new/improved process requirements. In many cases thermometer performance must be evaluated both for accuracy and precision by direct comparison with the International Temperature Scale of 1990 (ITS-90). Additionally, such performance demonstration, i.e., traceability to ITS-90, enhances the acceptability of new thermometry technologies both domestically and in international markets where such traceability is a requirement of use.

***Economic Significance of Innovation*:** Manufacturing processes in the petrochemical, pharmaceutical, semiconductor, and other industries depend upon chemical reactions having strong temperature dependencies. Process temperature strongly affects efficiencies and/or product quality. Thermometer performance often has the potential to "make or break" development of a new process technology, particularly those that depend upon accuracy to replicate process performance from one installation or site to the next. Calibration uncertainties may be incorrect by as much as 50 % in severe cases, the impact can be high because. Costs incurred by malfunctioning processes are difficult to estimate.

***Technical Barrier to the Innovation*:** Existing standards are accurate for the large majority of industrial needs and they span the required temperature range. The barriers to effective dissemination at increased accuracies of these standards are the lack of simple, efficient, validated processes to assure measurement confidence on the factory floor. Today, temperature calibrations require multiple types of apparatus to cover multiple temperature ranges; sensor degradation in process industries is difficult to diagnose because transfer standards are fragile and prone to degradation; and the uncertainties of commercial devices are rarely determined with rigor.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** Procedures: effective methods to conduct proficiency testing in industrial environments and to evaluate sensor degradation either do not exist or do not have sufficient performance. Equipment: there is a need for artifact standards and thermal environments used for calibration that require reduced skill to use and have increased flexibility and durability.

***Potential Solutions to Measurement Problem*:** Potential solutions are natural extensions complementary to NIST's temperature calibration services, particularly for the most stringent requirements. Solutions include: (1) proficiency testing to efficiently validate the performance of industrial calibrations, (2) documentary standards and supporting research that provide simple, cost-effective methods of characterizing sensor performance and degradation, and (3) isothermal calibration environments that span broad temperature ranges. Isothermal enclosures would benefit from the development of novel, thermally anisotropic materials.

Case Study – Measurement Needs

***Technology at Issue*:** Advanced Humidity Sensors to Optimize Fuel Cell Operation

***Submitter*:** Dean Ripple

***Technological Innovation at Stake*:** Fuel cells are the preferred means of converting hydrogen and hydrogen-rich gases to electrical power for automotive and other applications in the future. Humidity measurement and control is crucial for efficient operation of proton-exchange-membrane fuel cells (PEMFC), presently the dominant fuel cell technology under development. PEMFC systems are most efficient at temperatures up to 150 °C, and relative humidity greater than 95%. The latter is a challenging measurement that must be made in atmospheres that can adversely affect sensor performance. Small deviations from the humidity set point significantly reduces PEMFC efficiency and has potential for damage to the membrane itself.

***Economic Significance of Innovation*:** Present sales of fuel cell systems are $330M/yr. Research and development focuses on PEMFC systems, approximately 55% of total effort, particularly for potential automotive use. Fuel cells are more efficient that internal combustion engines, are non-polluting, and mechanically simpler. Successful development of PEMFC fuel cells for automotive use is expected to rival the $60B/yr internal combustion engine market that would be eclipsed by a successful technology.

***Technical Barrier to the Innovation*:** To achieve humidity control levels necessary for optimized PEMFC operation, improved humidity measurement technology is required. Humidity sensor technologies presently in use for fuel cells have been adapted from other applications. In use, these have proven insufficiently durable and are error prone when exposed to water droplets commonly found near optimum operating points for PEMFCs. Robust sensing technologies capable of reliable operation under these conditions must be developed. Performance demonstration of the advanced sensor technologies requires humidity standards capable emulating the operating temperatures and humidity levels. Both the humidity sensing technologies and the standards that would support demonstration of their performance currently exist.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** New sensor technology must be compatible with high operating temperatures, insensitive to water saturation by occasional water droplets or condensation, have sufficient accuracy to enable operation close to the condensation limit, and be of low cost for implementation in production PEMFC systems. Technology for new humidity standards should avoid the large-volume water vessels used in present humidity generators and be compatible with hydrogen and oxygen gas streams, as well as the traditional gas stream, air, used in current humidity standards.

***Potential Solutions to Measurement Problem*:** To avoid fouling by water droplets, future sensors must have internal heating or rely on an active sensing surface, rather than a water-sensitive bulk material. Several candidate sensors, based on capacitance variations or surface acoustic waves, are presently in the development stage. For humidity standards, a robust, primary hygrometer may be made using a radio-frequency cavity resonator approach, which has a resonant frequency that varies with water concentration in a well-understood manner. With a primary hygrometer available, flowing moist gas from a relatively simple humidity generator and comparing the sensor reading with the primary hygrometer reading provide a means for sensor performance evaluation.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Distribution of accurate and auditable time signals for time-stamping legal and financial transactions

***Submitter*:** Tom O'Brian

***Technological Innovation at Stake*:** As electronic legal and financial transactions are increasingly used for improved efficiency and enhanced functionality, a major challenge in ensuring auditable records of these cyberspace transactions is providing an auditable, authenticated, accurate time source to synchronize time-stamping devices across the world. Only modest accuracy is usually required – one second or so – which can be easily achieved. For example, The National Association of Security Dealers (NASD) operates its Order Audit Trail System (OATS) to track all events in investor orders and transactions and to monitor trading practices of brokerage firms. OATS requires that all transaction events must be timestamped with devices – whether manual devices or electronic timestamps – "synchronized to a source that is synchronized to within three seconds of the National Institute of Standards' (NIST) atomic clock." [NASD OATS Rule 6953].

***Economic Significance of Innovation*:** The use of electronic timestamping is widespread and rapidly growing. As noted above, NASD requires that all transactions from its 600,000 member businesses be accurately timestamped against an auditable source, including the many billions of dollars of financial transactions on the NASDAQ exchange every business day. Many other companies and organizations are providing or developing electronic timestamping services that can be audited and authenticated, including the U.S. Postal Service's Electronic Postmark (EPM) program.

***Technical Barrier to the Innovation*:** The principal challenge is ensuring the broad distribution of synchronization signals is continuously available, easily used by millions of different customers with varying needs, and that the synchronization source is highly resistant to tampering, spoofing, or other intentional disruption for purposes of fraud, mischief, or other malicious intent. For example, NIST and other organizations distribute time over the Internet which easily meets the requirements for one second accuracy, broad distribution, and ease of use. NIST currently serves 1.6 billion requests per day to synchronize computer clocks and other electronic timekeeping devices to official U.S. time. But these sources are in principle not secure or auditable. Individual service providers using proprietary technologies provide solutions for a fee for individual applications. But it is often difficult or impossible to determine the accuracy and security of these proprietary solutions.

***Stage of Innovation Where Barrier Appears*:** End Use

***Measurement-Problem Part of Technical Barrier*:** The primary required measurement service is provision of broadly distributed sources of authenticated and auditable time referenced to NIST and/or the U.S. Naval Observatory, the only sources of official U.S. time.

***Potential Solutions to Measurement Problem*:** NIST and other organizations have developed potential solutions for broad and secure distribution of authenticated time, including ideas patented by NIST.

Case Study – Measurement Needs

***Technology at Issue*:** Chip-Scale Atomic Clocks

***Submitter*:** Tom O'Brian

Technological Innovation at Stake: The goal is to develop ultraminiature atomic frequency references (atomic clocks and related devices) that are about the size of a computer chip, can be mass produced at modest cost, and outperform by 1,000 times or better the quartz oscillators that currently serve as small frequency references. These so-called chip-scale atomic devices (CSADs – the entire device is comparable in size to a computer chip and is produced using standard semiconductor device fabrication technology) have the potential to revolutionize portable electronic applications, including: higher performance GPS receivers resistant to jamming; higher performance wireless communications with improved security; portable magnetometers almost as sensitive as laboratory research based instruments; and extremely sensitive gyroscopes for inertial navigation. CSADs not only dramatically outperform quartz, but open new applications (magnetometry, gyroscopes), not possible with quartz.

***Economic Significance of Innovation*:** If successful, CSADs could replace quartz in every high-end application: a CSAD in every GPS receiver, in every wireless communications device (including cell phone handsets), etc. And the higher performance of CSADs relative to quartz would likely help expand the existing GPS receiver market and wireless telecommunications market. In addition, CSADs would open new markets such as portable, high sensitivity magnetometers for mineral exploration, security (detection of concealed weapons, detection of magnetic fields associated with equipment in hidden tunnels, etc.), biomedical imaging, ad hoc location systems, and other applications; and the potential to make inertial navigation devices so small that every soldier and emergency responder could be equipped with a combination GPS/inertial navigation device to continually provide accurate positioning information even inside buildings, underground, or in "urban canyons" where GPS service is not available.

***Technical Barrier to the Innovation*:** The technical barrier is developing an all optical, ultraminiature atomic frequency reference based on tiny lasers and detectors, and developing new methods of fabricating tiny cells containing the active atomic standards.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Developing measurement facilities and protocols to determine CSAD performance (short-term and long-term frequency stability, factors that limit performance), power consumption, and the success rate of processes to mass produce CSADs at a reasonable unit cost.

Potential Solutions to Measurement Problem: Researchers are actively developing and optimizing prototype CSADs and beginning to explore manufacturing solutions. For example, Symmetricom, a major manufacturer of network synchronization equipment is producing an initial run of miniature atomic clocks for timing applications, and the Navy Space and Navigation Warfare Systems Center in San Diego is experimenting with incorporating prototype chip-scale atomic clocks into GPS receivers to enhance performance.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Optical Time & Frequency Standards

***Submitter*:** Tom O'Brian

Technological Innovation at Stake: The increasing demands for tighter synchronization and higher performance will lead to the introduction in the next few years of optical atomic time and frequency standards. The measurement and distribution of highest accuracy time and frequency critically enables such technologies as Global Position System (GPS)-based positioning and navigation, precision timing for telecommunications, synchronization of satellite communication networks, and scientific research to develop future technologies. Today's best atomic time and frequency standards (atomic clocks) are based on microwave transitions. Optical atomic time and frequency standards will outperform the best microwave standards by a factor of 10 to 100.

***Economic Significance of Innovation*:** Accurate time, frequency, and synchronization are crucial infrastructures underpinning such technologies as GPS, telecommunications, high-speed computing and many other core technologies. Limitations in distribution of the highest accuracy time and frequency limit long-term improvements in these and many other systems.

***Technical Barrier to the Innovation*:** The current best microwave distribution technology is barely adequate to permit distribution of time and frequency information from the world's best atomic clocks. No system for highest accuracy distribution of optical time and frequency information exists. Optical time and frequency information is distributed over fiber optic networks, but currently with far less accuracy than required to support future needs.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Measurements are needed to support research and development of new optical systems for distributing the highest accuracy time, frequency, and synchronization information through optical signals. Better understanding of timing jitter and noise in fiber optic systems is required, along with measurements of new optical and electronic components and technologies that optimize timing accuracy.

Potential Solutions to Measurement Problem: New ways of measuring the performance of fiber optic systems based on the technology of femtosecond laser frequency combs is under development. These combs can generate extremely precise signals from the microwave to the optical range with exquisite control. Researcher can explore the use of these combs to tightly control the wavelength (frequency), power, and shape of timing pulses on fiber optic networks to optimize time and frequency distribution.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue**:** Ultrafast Electronic Communications

Submitter**:** Tom O'Brian

Technological Innovation at Stake: Many applications for homeland security, defense, and commerce require the use of synchronized ultrafast electronic communications. Applications currently under development require synchronized ultrafast electronic communications with ultra-low noise include new surveillance technologies, ultra-high-speed computing, advanced communications, novel imaging systems, and new defense ranging and positioning systems.

Economic Significance of Innovation**:** The ability to dramatically reduce noise in a wide range of applications would significantly impact many defense applications (surveillance, radar, navigation, remote monitoring and control of the battlefield, etc.), wireless telecommunications, high-speed computing, and new imaging systems under development (difficult to quantify the impact but likely many billions of dollars annually).

Technical Barrier to the Innovation**:** New high performance surveillance, telecommunications, computing, and electronic applications require reduction of noise in the microwave and optical regions by up to 10,000 times over current state-of-the-art. The primary types of noise of interest include instantaneous deviations from the required frequency or "jitter," and instantaneous variations in the signal power or amplitude. In both cases, the interest is intrinsic noise in the systems themselves limiting device performance, as opposed to noise from external sources. When even a few such components are linked together in computers or telecommunications systems, the best performance of the system is limited by the lack of synchronization to far below 100 GHz. To dramatically improve such applications, substantial reductions in jitter noise are required.

Stage of Innovation Where Barrier Appears**:** R&D

Measurement-Problem Part of Technical Barrier**:** The required ultra-low noise performance can only be achieved and verified by substantially improving the state-of-the-art in noise measurement – up to 10,000 times more sensitive than is currently available anywhere in the world. The main frequency ranges of interest are from the higher ranges of the microwave (10^{10} cycles per second) to the optical frequency range (10^{15} cycles per second). New high-performance systems can't be developed, tested, and verified if their performance can't be measured to determine if specifications are being met.

Potential Solutions to Measurement Problem: Researchers are developing new ways of measuring ultralow noise in systems based on the technology of femtosecond laser frequency combs. These combs can generate extremely precise signals from the microwave to the optical range with exquisite control. The potential for these combs to make microwave noise measurements nearly 10,000 more sensitive than current state-of-the-art in electronic measurements has been recently demonstrated. But additional research and development is needed to transform this promising technology to reality.

Technology at Issue**:** Automotive Hydrogen Fuel Cells

Submitter**:** John Slotwinski

Technological Innovation at Stake**:** All automotive manufacturers intend to mass-produce and mass-market hydrogen-powered vehicles within the next decade. A leading contender technology for these types of vehicles is the employment of polymer-electrolyte-membrane (PEM) fuel cells, running on hydrogen, to provide a source of electrical energy.

Economic Significance of Innovation**:** Hydrogen-powered automobiles would greatly reduce both the emission of greenhouse gases into the atmosphere and the reliance on limited, traditional fossil-based fuels mainly from foreign sources, which have been predicted to be depleted within 50 years. The impact of this could be enormous, considering that some 17 million cars are sold in the U.S. each year.

Technical Barrier to the Innovation**:** Current PEM fuel cells are neither efficient enough nor robust enough for widespread use. PEM fuel cells running on hydrogen and air produce only water and heat as byproducts and zero greenhouse gas emissions. While some water is needed to keep the membrane moist, an abundance of water can flood the membrane and render it ineffective. Understanding and managing the water production, and making design improvements based on this, is critical for both peak performance and enhancing the PEM lifetime.

Stage of Innovation Where Barrier Appears**:** R&D

Measurement-Problem Part of Technical Barrier**:** Fuel cells are made of high charge density metals and other materials that prevent all conventional means of non-destructive measurement, other than neutron imaging, from analyzing the operational characteristics of the fuel cell. A detailed measurement and analysis of the production and movement of hydrogen, oxygen, electrons, heat, and water in this system is required in order to optimize fuel cell performance and lifetime.

Potential Solutions to Measurement Problem**:** R&D to find a practical way to use capabilities of current measurement instrumentation.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Coordinate-Measuring-Machine Alternatives

***Submitter*:** John Slotwinski, Robert Ivester

***Technological Innovation at Stake*:** 3D Volumetric X-Ray and 3D Optical Scanning methods offer the potential for high-resolution 3D density measurements of parts, as an alternative to using the coordinate measuring machines (CMMs) currently used by the automotive original equipment manufacturers (OEMs). These methods are potentially capable of capturing quantities of data greater than or equal to that provided by CMM measurements but in significantly less time.

***Economic Significance of Innovation*:** During the production cycle, OEMs use CMMs for quality control of high-value cast parts such as engine casings, cylinder heads, and transmission cases. Despite their high-accuracy, CMM-measurements are time-consuming, require specialized environments, and cannot be done in a manufacturing environment, resulting in added production time and cost. U.S. automotive OEMs employ roughly four hundred CMMs, each of which requiring a specialized environment costing approximately $75,000 per year to maintain.

***Technical Barrier to the Innovation*:** 3D Volumetric X-Ray and 3D Optical Scanning methods offer the potential for rapid, high-resolution 3D density measurements of parts in a manufacturing environment, yet generate huge datasets (often 3GB+ per scan). Data analysis of these datasets is time consuming and it is difficult and time-consuming to construct 3D models out of the datasets.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** In order to successfully deploy 3D Volumetric X-Ray and 3D Optical Scanning methods the OEMs need to be able to perform quick analyses on the enormous datasets generated by these technologies.

***Potential Solutions to Measurement Problem*:** Develop new mathematical algorithms that allow for quick analyses of the enormous datasets generated by these technologies.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Sheet metal forming

***Submitter*:** Timothy Foecke

***Technological Innovation at Stake*:** To meet its goals for fuel efficiency, the US automotive industry is moving to lighter, high-strength materials for auto bodies. Advanced sheet metal technology is one of several different advanced material technologies that the automotive industry is considering for the future. However, their lack of experience in forming these materials translates into difficulty in making accurate dies for producing body parts.

***Economic Significance of Innovation*:** Typical design and development of dies require 6-12 iterations, and up to 12 months, to make them right, costing the auto industry $700M per year. Removing even a single iteration from the stamping die production cycle by using more accurate material properties has the potential to save millions of dollars from typical auto body panel development costs.

***Technical Barrier to the Innovation*:** Finite element models of forming dies do not have material property information of sufficient sophistication to accurately predict die shapes that will produce a given part. Data are needed regarding multi-axial yield loci of sheet metals, and how they evolve with plastic strain, in order to validate or modify commonly used numerical models of sheet metal behavior. This requires an entirely new set of experiments and associated metrology.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** Measuring the stress in a metal sheet while it is being loaded in some multi-axial plastic strain states is a difficult task. If the stress is calculated based on the definition of applied load divided by cross-sectional area, defining these terms can be very difficult if there are unknowable frictional components or if the sample is of a complex or non-uniform shape. Modifying the sheet through thinning or other sample preparation techniques must be avoided so that the measurements can be related back to sheet metal as it will be used in production.

***Potential Solutions to Measurement Problem*:** New measurement techniques for determining the stress states of materials during sheet metal forming and standard test methods tied to those techniques.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** Automotive coatings

***Submitter*:** Tinh Nguyen

***Technological Innovation at Stake*:** Recently, the coatings industry has formulated coatings with metal oxide nanoparticles that act not only as ultraviolet absorbers but also improve the scratch and mar resistance of a coating. Substitution of these metal oxides for their organic photostabilizer equivalents could dramatically reduce the cost of coatings.

***Economic Significance of Innovation*:** Consumers often decide not to buy a particular car based solely on the car's appearance. The appearance of a vehicle at the end of its useful life is also an important factor in a consumer's willingness to buy the next car from the same manufacturer. The global automotive coatings market is $3 billion per year

***Technical Barrier to the Innovation*:** The auto part industry cannot improve coatings products since they cannot measure their properties with good precision. In recent years, automotive companies have employed special effects pigments, aluminum flakes and interference pigments, to differentiate their products from those of their competition. The effect that these pigments have on the aging of a coating is unknown. All automotive coatings are formulated with photostabilizers to protect the coating from weathering. These organic photostabilizers are expensive.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** Metrologies for measuring the effectiveness of these additives on appearance and weathering are not available so that implementation of this technology has been hampered. Metrological advances are needed for measuring initial and aged coating appearance, for measuring coating scratch resistance, for measuring interfacial adhesion, and metrology for measuring the nanomechanical properties.

***Potential Solutions to Measurement Problem*:** Providing reliable, scientific-based metrologies and methodologies that can effectively measure the performance and service life of automotive coatings will enable the raw materials suppliers, coatings formulation producers, and end users (automobile companies and auto part companies) the necessary tools to adequately specify products and provide warranties with certainty. Develop and standardize these metrologies and methodologies based on sound scientific principles.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Advanced Vehicle Safety Systems

***Submitter*:** Maris Juberts

***Technological Innovation at Stake*:** The automotive industry is beginning to develop advanced integrated driver assist systems which use information from multiple real-time sensors mounted on vehicles and on roadways to help drivers avoid the most common types of deadly crashes. The focus on preventing crashes is a new direction for the Department of Transportation (DOT) safety programs and its associated stakeholders. Currently, appropriate sensor systems and methods for doing this have not been fully proven.

***Economic Significance of Innovation*:** About 5.4 million rear-end, run-off-the-road, lane change, and crossing path collisions occur every year in the U.S based on police-reported crash statistics. This results in more than 27,000 deaths and more than 2.6 million injuries per year. These crashes cost the U.S. economy more than $230 billion a year and consume a greater share of national healthcare costs than any other single cause of illness or injury. The DOT predicts that if new crash prevention systems are properly deployed on all new vehicles, 1 million target crashes could be prevented every year. This could potentially result in about $50 billion in cost savings every year. In addition, introduction of this technology into the U.S. automotive market could strengthen U.S. industrial competitiveness in the global marketplace.

***Technical Barrier to the Innovation*:** The technical challenge is for systems to collect and analyze data from a large number and type of sensors, and make intelligent decisions based on that data, all in real-time. Before getting authorization to use this technology on new cars and other vehicles that are sold in the U.S., the developers of advanced active crash prevention systems must convince the National Highway Traffic Safety Administration (NHTSA, a Department of Transportation regulatory agency) that this technology provides benefits to safety and meets accepted performance criteria.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Accurate real-time reference data measurement techniques and objective test procedures necessary to characterize system response and evaluate benefits to safety of advanced sensor-based crash prevention systems in near crash (naturalistic) driving scenarios do not exist.

***Potential Solutions to Measurement Problem*:** Develop independent measurement systems for validating performance and effectiveness of advanced crash prevention technology under development by industry teams. The steps needed to evaluate the benefits to safety include development of crash imminent scenarios, evaluation of data needs from field operational tests, design of field experiments, and the development of test procedures and the data measurement systems to verify system performance.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** 42-Volt Automotive System

***Submitter*:** John Slotwinski

***Technological Innovation at Stake*:** Automotive manufacturers are transitioning from 14-Volt systems to a new 42-Volt architecture, which will result in automobiles that have improved fuel efficiency and reduced emissions.

***Economic Significance of Innovation*:** By 2010 the annual production of 42-Volt vehicles worldwide is projected to be 13 million units. 42-Volt systems will allow for the elimination of today's inefficient mechanical and electrical systems. They will be replaced with new technologies (such as steer-by-wire, break-by-wire, integrated starter-generators, and electromagnetic engine valve systems) that will improve overall fuel efficiency and reduce emissions.

***Technical Barrier to the Innovation*:** A potential fire hazard, due to arcing, exists when polymeric materials are used for automotive switches and electrical connectors at the 42-Volt level.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Industry currently has no reliable and reproducible arcing test for polymeric materials used in automotive applications.

***Potential Solutions to Measurement Problem*:** Industry needs a repeatable and reproducible arcing test, for the type of polymeric materials that are used in automotive applications, which adequately simulates a 42-Volt electrical environment.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Modeling of Flexible Parts

***Submitter*:** John Slotwinski

***Technological Innovation at Stake*:** The U.S. automotive industry lacks efficient virtual tools to predict the behavior of flexible parts and tooling such as rubber hoses, wiring harnesses and robot dress. With these tools automotive manufacturers could virtually predict the size and shape of flexible parts in the large assembly modeling and digital mock-ups that are typically done for automobile designs. This would result in faster design-to-production times and detection of design errors involving flexible parts in a virtual, as opposed to physical, environment.

***Economic Significance of Innovation*:** Design errors involving flexible parts are typically discovered during physical prototyping, which is an expensive and time-consuming step of automotive manufacturing. The U.S. automotive "Big-3" would save at least $120 million over the next 10 years in prototyping and redesign costs if these errors were discovered during the design stage.

***Technical Barrier to the Innovation*:** Software to adequately model flexible parts does not exist. Because of this designers and manufacturers must instead rely on experience, trial-and-error, and physical prototypes in order to determine the size and shape of flexible parts.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** Adequate modeling software for flexible parts requires verified material property data for input into the software, new algorithms, and methods for physical validation of the predicted, virtual results.

***Potential Solutions to Measurement Problem*:** Solutions include an industry-endorsed database of material property data, development of new algorithms, and consensus, industry-accepted methods for physical validation of the predicted, virtual results.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue**:** Metrology Equipment Interoperability

Submitter**:** Ron Grajewski (GM)

Technological Innovation at Stake**:** U.S. automotive manufacturers cannot easily incorporate new metrology equipment into their vehicle production stages. This metrology equipment is needed for testing new vehicles to current regulatory requirements, new regulatory requirements, and vehicle design specifications. Hardware interoperability, where users could plug-and-play the hardware components of their choice, would allow for complete inter-device communication and thus reduce costs and allow for best-in-class component choices.

Economic Significance of Innovation**:** Automotive manufacturers must spend significant time and money customizing various pieces of test equipment to interoperate and interface. These interoperability problems cost the U.S. automotive industry at least $1B per year.

Technical Barrier to the Innovation**:** Test equipment suppliers currently do not work together on a common interface and common solution. Test equipment available from vendors do not have common interfaces and common data for data acquisition applications. The automotive manufacturers must develop customized solutions in order to share test results between multiple pieces of test equipment.

Stage of Innovation Where Barrier Appears**:** Production

Measurement-Problem Part of Technical Barrier**:** Measurement data results do not have a common output format. Methods for testing data formats to an industry-accepted format (e.g., conformance testing) are needed.

Potential Solutions to Measurement Problem**:** The Europe-based Association for Standardization of Automation and Measuring Systems (ASAM) forum is the only organization that is currently addressing this issue, by providing guidance on a generic data standard format. However, it is not a complete solution and is not acceptable to all metrology equipment users. Metrology testbeds to test for conformance are also needed, once an industry-accepted standard has been developed.

Case Study – Measurement Needs

Technology at Issue: In-line Inspection and Factory Control Equipment

***Submitters*: **Herbert Bennett, for industry

***Technological Innovation at Stake*:** The International Technology Roadmap for Semiconductors anticipates broad industry manufacture of 22 nanometer integrated circuits, which will have minimum features of ~ 10 nm by 2016. Early developers will start on this technology within the next two years; however, in-line factory process control equipment for making sub-32 nm circuits is not available.

***Economic Significance of Innovation*:** The Semiconductor Industry Association's economic forecast calls for 2005 sales to increase by 6.8 percent to $227.6 B, followed by increases of 7.9 percent to $245.5 B in 2006, 10.5 percent to $271.3 B in 2007, and 13.9 percent to $309.2 B in 2008. Introducing integrated circuits with higher density increases computing speed and reduces the cost of components for computing and a wide range of applications. If the rate of technology innovation stops or slows dramatically, there will be a slowing in the introduction of new computing and consumer electronics and this will dramatically reduce growth in the semiconductor sector and other sectors that depend on semiconductor advances.

***Technical Barrier to the Innovation*:** Device features already have nano-sized dimensions and high aspect ratios. Developing and manufacturing devices at these sizes and aspect ratios require advanced in-line and real-time factory control systems that monitor processing steps to make certain that critical processing parameters remain within acceptable tolerances. Such factory control equipment with integrated characterization and metrology tools for measuring interfacial, structural, and materials properties on nano-sized devices does not exist.

***Stage of Innovation Where Barrier Appears*:** R&D and production

***Measurement-Problem Part of Technical Barrier*:** Next generation control and monitoring equipment needs new characterization and metrology tools that measure at the nanoscale interfacial, structural, and materials properties of ultra-thin films and nano-wire sized lines with the required resolution. These tools are either unavailable or in early development. Examples include optical measurements of thin layers and interfaces.

***Potential Solutions to Measurement Problem*:** Develop manufacturing worthy, high throughput methods such as optical metrology from the far IR to VUV, X-ray reflectivity, small angle X-ray scattering, X-ray diffraction, X-ray photoelectron spectroscopy, and Auger electron spectroscopy. In addition, develop electrical metrology for new materials such as high speed atomic force microscopy.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** In-line/Real-time Analytic Tools for Measuring Sub-10 nm Defects

***Submitters*:** Herbert Bennett, for industry

***Technological Innovation at Stake*:** In-line/real-time detection, review, and analysis of sub-10 nm defects and particles on patterned and un-patterned wafers. The International Technology Roadmap for Semiconductors anticipates that the broad industry manufacture of integrated circuits based on the 22 nanometer technology generation will have minimum features of ~ 10 nm by 2016. Early developers will start on this technology within the next two years; however, tools to measure critical dimensions are not capable of being used as in-line monitors.

***Economic Significance of Innovation*:** The Semiconductor Industry Association's economic forecast calls for 2005 sales to increase by 6.8 percent to $227.6 B, followed by increases of 7.9 percent to $245.5 B in 2006, 10.5 percent to $271.3 B in 2007, and 13.9 percent to $309.2 B in 2008. Introducing integrated circuits with higher density increases computing speed and reduces the cost of components for computing and a wide range of applications. If the rate of technology innovation stops or slows dramatically, there will be a slowing in the introduction of new computing and consumer electronics and this will dramatically reduce growth in the semiconductor sector. When defect or particles are not detected, the yield of integrated circuits is reduced below that required for economically viable manufacturing.

***Technical Barrier to the Innovation*:** Metrology tools to detect particles and defects are incapable of measuring defects or particles for sub-32 nm technology generations with a high capture rate and with precise and accurate sizing on the manufacturing line.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The integrated circuit industry requires processes that produce hundreds of billions of features uniformly across each wafer for each mask operation with a tight distribution of sizes. The inability to detect particles or defects on a large number of chips per wafer and wafers per lot will dramatically slow the development of integrated circuit technology.

***Potential Solutions to Measurement Problem*:** Perform R&D to extend conventional e-beam and optical based defect detection tools. Evaluating progress will require standardized and patterned wafers with defects and particles several generations ahead of the leading-edge manufacturing of integrated circuits. The solution must include reference materials to test R&D progress.

Technology at Issue**:** Dopant Distribution Instrumentation

Submitters**:** Herbert Bennett, for industry

Technological Innovation at Stake**:** Instrumentation for determining 3D dopant distributions in wafers and epilayers (dopant distribution mapping) for sub-22 nm processing technologies. The International Technology Roadmap for Semiconductors anticipates broad industry manufacture of the 22 nanometer integrated circuits, which will have minimum features of ~ 10 nm by 2016. Early developers will start work on this technology within the next two years; however, current tools to measure 3D dopant distributions at the nanoscale are not capable of being used as in-line monitors.

Economic Significance of Innovation**:** The Semiconductor Industry Association's economic forecast calls for 2005 sales to increase by 6.8 percent to $227.6 B, followed by increases of 7.9 percent to $245.5 B in 2006, 10.5 percent to $271.3 B in 2007, and 13.9 percent to $309.2 B in 2008. Introducing integrated circuits with higher density increases computing speed and reduces the cost of components for computing and a wide range of applications. If the rate of technology innovation stops or slows dramatically, there will be a slowing in the introduction of new computing and consumer electronics and this will dramatically reduce growth in the semiconductor sector and other sectors that depend on semiconductors.

Technical Barrier to the Innovation**:** There is a lack of adequate instrumentation to measure in real-time and in-line 3D dopant distributions in wafers and epilayers for sub-22 nm technologies. Device features already have nano-sized dimensions. Developing and manufacturing devices at these sizes in high volume require characterization and metrology tools that give 3D dopant distributions and structural and material properties with atomic resolution.

Stage of Innovation Where Barrier Appears**:** R&D and production

Measurement-Problem Part of Technical Barrier**:** Develop characterization and metrology tools that measure dopant concentration, location, and activation. Such tools are just becoming capable of near atomic resolution. Examples include aberration corrected scanning transmission electron microscopy (STEM) and local electrode atom probes (LEAP). Dopant location in the smallest transistors such as FINFETS is almost impossible to determine.

Potential Solutions to Measurement Problem**:** The solution includes working to improve resolution of new characterization and metrology tools such as aberration-corrected STEM, LEAP, STEM, scanning capacitance microscopy, spreading resistance measurements at the nanoscale, and secondary ion mass spectroscopy (SIMS) of small structures and thin films for dopant measurements.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue**:** Interfacial Characterization Instrumentation

Submitters**:** Herbert Bennett, for industry

Technological Innovation at Stake**:** Advanced, beyond next generation, instrumentation to measure electronic properties of sub-22 nm materials and devices**.** The International Technology Roadmap for Semiconductors anticipates broad industry manufacture of integrated circuits, based on the 22 nanometer technology generation, which will have minimum features of ~ 10 nm by 2016. Early developers will start on this technology within the next two years; however, tools to measure precisely and accurately interfacial properties are not capable of being used as in-line monitors.

Economic Significance of Innovation**:** The Semiconductor Industry Association's economic forecast calls for 2005 sales to increase by 6.8 percent to $227.6 B, followed by increases of 7.9 percent to $245.5 B in 2006, 10.5 percent to $271.3 B in 2007, and 13.9 percent to $309.2 B in 2008. Introducing integrated circuits with higher density increases computing speed and reduces the cost of components for computing and a wide range of applications. If the rate of technology innovation stops or slows dramatically, there will be a slowing in the introduction of new computing and consumer electronics and this will dramatically reduce growth in the semiconductor sector and in many other sectors that depend on semiconductor advances.

Technical Barrier to the Innovation**:** Incomplete understanding of the physical and chemical processes limits the rate of progress in developing appropriate instrumentation. Device features already have nano-sized dimensions. Developing and manufacturing devices at these sizes requires characterization and metrology tools that measure interfacial, structural and materials properties on nano-sized devices. Such tools are not available for high-volume and high-quality manufacturing with high yields.

Stage of Innovation Where Barrier Appears**:** R&D

Measurement-Problem Part of Technical Barrier**:** Characterization and metrology tools that measure interfacial, structural and materials properties of ultra-thin films and nano-wire sized lines with the required resolution, precision, and accuracy are either unavailable or in early development and not available to industry. Examples include optical measurements of thin layers and interfaces.

Potential Solutions to Measurement Problem**:** Develop metrology tools from the far IR to VUV to X-ray. Examples include polarized reflectivity, spectroscopic ellipsometry, non-linear optical methods such as second harmonic generation, X-ray reflectivity, small angle X-ray scattering, X-ray diffraction, X-ray photoelectron spectroscopy, Auger electron spectroscopy such as co-incidence methodologies, and higher energy resolution backscattering methods.

Case Study – Measurement Needs

***Technology at Issue*:** Atomic Mapping Instrumentation

***Submitters*:** Herbert Bennett, for industry

***Technological Innovation at Stake*:** Advanced atomic mapping instrumentation for structural and compositional analyses at the nanoscale for sub-22 nm generations. The International Technology Roadmap for Semiconductors anticipates broad industry manufacture of integrated circuits based on the 22 nanometer technology generation, which will have minimum features of ~ 10 nm by 2016. Early developers will start working on this technology within the next two years; however, tools for structural and compositional analyses are not capable of being used as in-line monitors.

***Economic Significance of Innovation*:** The Semiconductor Industry Association's economic forecast calls for 2005 sales to increase by 6.8 percent to $227.6 B, followed by increases of 7.9 percent to $245.5 B in 2006, 10.5 percent to $271.3 B in 2007, and 13.9 percent to $309.2 B in 2008. Introducing integrated circuits with higher density increases computing speed and reduces the cost of components for computing and a wide range of applications. If the rate of technology innovation stops or slows dramatically, there will be a slowing in the introduction of new computing and consumer electronics and this will dramatically reduce growth in the semiconductor sector and will have a negative ripple effect on many other economic sectors that depend on advance semiconductors.

***Technical Barrier to the Innovation*:** Device features already have nano-sized dimensions. Adequate characterization and metrology tools that measure structural and materials properties with atomic resolution do not exist. Such tools are needed to develop and manufacture devices at these sizes.

***Stage of Innovation Where Barrier Appears*:** R&D and production

***Measurement-Problem Part of Technical Barrier*:** Improving resolution and precision of atomic mapping instrumentation. True atomic resolution in 3D must become routine for the entire range of materials and structures. Characterization and metrology tools that are just becoming capable of near atomic resolution include aberration corrected transmission electron microscopes, local electrode atom probes, and scanned probe microscopes. In addition to the hardware, simulations of the measurement and the measurement system are required for the considerable amount of new phenomena associated with nano-sized dimensions. Tomography of structural features must be extended beyond the large feature capability presently available.

***Potential Solutions to Measurement Problem*:** Improving resolution and precision from near atomic resolution to true atomic resolution by developing next generation aberration corrected electron microscopes such as scanning electron microscopes and transmission electron microscopes (TEM), and scanning TEM, and scanned probe microscopes such as atomic force microscopes, scanning potential microscopes, scanning near field acoustic microscopes, scanning thermal microscopes, and local electrode atom probes.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Next-generation optical microscopes

***Submitters*:** Herbert Bennett, for industry

***Technological Innovation at Stake*:** Advanced, beyond next generation, near- and far-field optical microscopy for wafer inspection. The International Technology Roadmap for Semiconductors (ITRS) anticipates high-volume manufacture of integrated circuits based on the 22 nanometer technology generation, which will have minimum features of ~ 10 nm by 2016. Early developers will start working on this technology within the next two years; however, existing instrumentation to inspect wafers with such features and with acceptable resolution are not suitable as in-line monitors.

***Economic Significance of Innovation*:** The Semiconductor Industry Association's economic forecast calls for 2005 sales to increase by 6.8 percent to $227.6 B, followed by increases of 7.9 percent to $245.5 B in 2006, 10.5 percent to $271.3 B in 2007, and 13.9 percent to $309.2 B in 2008. Integrated circuits with higher densities increase computing speeds and reduce the costs of components for computing and many applications. If the rate of technology innovation stops or slows dramatically, there will be a slowing in the introduction of new computing and consumer electronics and this will dramatically reduce growth of the semiconductor sector and impact in a negative manner other economic sectors that depend on advanced semiconductors.

***Technical Barrier to the Innovation*:** Lack of high-resolution wafer inspection equipment for nanoscale devices and circuits. Device features already have nano-sized dimensions. Developing and manufacturing devices at these sizes requires wafer inspection instrumentation to verify that the wafers meet specifications, which are increasingly more stringent for each technology node of the ITRS, with acceptable tolerances before continuing with additional processing steps.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Optical microscopy has long been the most rapid means of imaging samples. Most lens designs for traditional optical microscopes do not use near-field light and thereby lose needed information about higher spatial-resolution details. High-resolution measurements are required to support advanced lens designs, especially for broadband light.

***Potential Solutions to Measurement Problem*:** The new sub-diffraction limited super-lens, such as the silver super-lens shows promise for extension of far-field optical imaging to well below the traditional resolution limits. In addition to demonstration and commercialization of this technology to single wavelength optical microscopes, work should include extension of this lens for a single wavelength to lens for broadband light and to alternative approaches for higher spatial-resolution optical imaging.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** Atomic Mapping Instrumentation

***Submitters*:** Herbert Bennett, for industry

***Technological Innovation at Stake*:** Atomic mapping instrumentation for sub-22 nm structural and compositional analyses of carbon based materials such as organic molecules and carbon nanotubes. The International Technology Roadmap for Semiconductors anticipates that new devices based on organic molecules or nanotubes may be needed to provide new device functions as complementary metal oxide semconductors (CMOS) approach sub-20 nm technologies.

***Economic Significance of Innovation*:** The Semiconductor Industry Association's economic forecast calls for 2005 sales to increase by 6.8 percent to $227.6 B, followed by increases of 7.9 percent to $245.5 B in 2006, 10.5 percent to $271.3 B in 2007, and 13.9 percent to $309.2 B in 2008. Introducing integrated circuits with higher density increases computing speed and reduces the cost of components for computing and a wide range of applications. If the rate of technology innovation stops or slows dramatically, there will be a slowing in the introduction of new computing and consumer electronics and this will dramatically reduce the growth in the electronic sector.

***Technical Barrier to the Innovation*:** Current transmission electron microscope (TEM) and scanning electron microscope (SEM) technologies cannot measure the location of carbon atoms to analyze the growth and operation of devices based on these materials.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Characterization and metrology tools that measure structural and materials properties are just becoming capable of near atomic resolution, but often can not measure the location of carbon, hydrogen and other light elements, due to small scattering cross sections.

***Potential Solutions to Measurement Problem*:** Develop aberration-corrected electron microscopes including scanning electron microscopes, transmission electron microscopes (TEM), scanning TEM.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Compound Semiconductor Cluster Tools

***Submitters*:** Herbert Bennett, Howard Hung, and James Maslar

Technological Innovation at Stake: Instrumentation with integrated software for cluster tools, which determines non-destructively in real-time and on-line whether III-V compound semiconductor materials meet specifications and are worthy for further processing, is needed to make next generation devices with greater figures of merit such as switching speeds and operating efficiencies.

***Economic Significance of Innovation*:** The global market for compound semiconductors exceeds $25 billion. III-V compound semiconductors enable many technologies that in turn provide large markets for silicon-based semiconductors. Examples include laser printers, cellular telephones and pagers, global positioning, DVD/CD players and recorders, laser fax machines, displays, and solid-state lighting. High-growth applications for devices based on III-V semiconductors continue. The semiconductor and chemical industry roadmaps call for next generation of III-V semiconductor processing cluster tools that quickly measure transport properties. Such tools are needed to reduce the cost per unit area and the cost per function and to increase yield and productivity. According to Intel, continuing Moore's law beyond 2015 will require using III-V semiconductors in main-stream applications to complement scaled silicon.

***Technical Barrier to the Innovation*:** The barriers are the lack of 1) adequate knowledge of III-V semiconductor transport properties needed for the design and manufacture of new-technology devices; 2) analytical tools that can measure these properties quickly for real-time process control during manufacturing; and 3) high-speed computing for extracting semiconductor transport properties from measured parameters and for simulating fabrication processes on-line.

***Stage of Innovation Where Barrier Appears*:** R&D and Production.

***Measurement-Problem Part of Technical Barrier*:** There is no equipment that accurately, non-destructively, cost effectively, and directly measures parameters related to device performance and to process control.

***Potential Solutions to Measurement Problem*:** Combining validated, robust theoretical models that are based upon robust quantum mechanical calculations, advanced computer simulations, and Raman spectra "will allow the semiconductor industry to go from what it can measure to what it needs, but can not measure. Raman spectroscopy requires minimal sample preparation and is particularly useful as a non-destructive technique. This theory and software will enable process engineers to extract in real-time transport properties from Raman spectra of III-V semiconductors.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Full System-on-Chip for Wireless Communications

***Submitters*:** Dylan Williams and Herbert Bennett

***Technological Innovation at Stake*:** The semiconductor industry requires new manufacturing processes and measurements with calibrated instruments to reliably characterize and limit the negative effects associated with crosstalk. As RF, digital, and analog/mixed-signal (AMS) circuits become smaller, more complex, and run at higher frequencies, crosstalk between different parts of the circuits increases dramatically as the electrical isolation between different parts decreases.

***Economic Significance of Innovation*:** The RF electronics industry is betting its future on reducing overall cost per function of its products and increasing functionality by more integration of RF, digital, and analog circuits. Public good areas that will benefit include first responders and health providers who use telemedicine. The market for semiconductors in cellular handsets is more than $20 billion, and about 38 % of this revenue comes from radio frequency and analog/mixed-signal ICs. The cellular handset semiconductor market itself represents almost 13 % of the total worldwide semiconductor market.

***Technical Barrier to the Innovation*:** The 2005 ITRS Chapter on RF and Analog Mixed-Signal Technologies for Wireless Communications says "Signal isolation may become the most difficult obstacle preventing full system-on-chip (SOC) implementation ….. it is difficult to agree on appropriate metrics for …signal isolation ….." The 2004 NEMI Roadmap cites "RF interference mitigation and shielding techniques" as gaps and showstoppers for handsets. In addition, crosstalk is a showstopper for computer backplanes and on-chip interconnects. The solutions proposed below for RF and AMS also will apply to computer backplanes and interconnects.

Stage of Innovation Where Barrier Appears: R&D and production

***Measurement-Problem Part of Technical Barrier*:** There are two types of systems for characterizing isolation and crosstalk in electrical ICs: high-impedance electrical probes and multiport network analyzers. Such systems provide information for mitigating RF interference and improving shielding. As the frequency of operation increases, the calibration of these instruments becomes extremely difficult. To date, no rigorous calibration procedures have been developed for either instrument.

***Potential Solutions to Measurement Problem*:** Develop new analyzers and new calibrations for high-impedance probes and high-frequency on-chip multiport network analyzers.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Sub-10 nm SEM Metrology Tools

***Submitter*:** Herbert Bennett, for industry

***Technological Innovation at Stake*:** In-line/real-time measurement tools for sub-10 nm features (critical dimensions (CD) - scanning electron microscopy (SEM) to support patterning for integrated circuits (ICs). The International Technology Roadmap for Semiconductors (ITRS) anticipates that the broad industry manufacture of the 22 nanometer (nm) IC technology generation will have minimum features of ~ 10 nm in 2016. Early developers will start development on this technology within the next two years; however, tools to measure critical dimensions are not capable of being used as in-line monitors.

***Economic Significance of Innovation*:** The Semiconductor Industry Association's economic forecast calls for 2005 sales to increase by 6.8 percent to $227.6 B, followed by increases of 7.9 percent to $245.5 B in 2006, 10.5 percent to $271.3 B in 2007, and 13.9 percent to $309.2 B in 2008. Introducing integrated circuits with higher density increases computing speed and reduces the cost of components for computing and a wide range of applications. If the rate of technology innovation stops or slows dramatically, there will be a slowing in the introduction of new computing and consumer electronics and this will dramatically reduce the growth in the electronic sector, which has considerable productivity implications for all economic sectors that rely on semiconductors. Furthermore, if the process has a large variation in feature sizes, the yield for circuit designs will be very low and this would dramatically increase the cost of products and make the new technology too costly for production.

***Technical Barrier to the Innovation*:** Metrology tools to measure critical features are incapable of measuring sub-20 nm features precisely and accurately within the manufacturing line. Thus, wafers must be sacrificed to destructive analysis to measure process dimensions outside of the wafer fabrication facility. Only a few samples will be characterized per operation, so significant information will be lost on the variability of the process in development.

Stage of Innovation Where Barrier Appears: R&D and production

***Measurement-Problem Part of Technical Barrier*:** The integrated circuit industry requires processes that produce 100's of billions of features uniformly across each wafer for each mask operation with a tight distribution of sizes. The inability to measure critical sub-20 nm features on a large number of features and wafers per lot will dramatically slow the development of integrated circuit technology.

***Potential Solutions to Measurement Problem*:** R&D to extend conventional e-beam based critical metrology tools. This would include aberration correction, brighter sources, and techniques to reduce dielectric charging on wafers.

***Technology at Issue*:** Sidewall Characterization Instrumentation

Submitters: Herbert Bennett, for industry

***Technological Innovation at Stake*:** Advanced instrumentation to characterize nanometer scale sidewall composition and roughness for sub-32 nm technologies. The International Technology Roadmap for Semiconductors anticipates broad industry manufacture of 22 nm integrated circuits, which will have minimum features of ~ 10 nm by 2016. Early developers will start development of this technology within the next two years; however, existing tools to measure sidewall composition and roughness are not capable of being used as in-line monitors.

***Economic Significance of Innovation*:** The Semiconductor Industry Association's economic forecast calls for 2005 sales to increase by 6.8 percent to $227.6 B, followed by increases of 7.9 percent to $245.5 B in 2006, 10.5 percent to $271.3 B in 2007, and 13.9 percent to $309.2 B in 2008. Introducing integrated circuits with higher density increases computing speed and reduces the cost of components for computing and a wide range of applications. If the rate of technology innovation stops or slows dramatically, there will be a slowing in the introduction of new computing and consumer electronics and this will dramatically reduce growth in the semiconductor sector.

***Technical Barrier to the Innovation*:** Lack of acceptable instrumentation to determine sidewall composition and aspect ratio. Device features already have nanometer-sized dimensions with high aspect ratios. Developing and manufacturing devices at these sizes and aspect ratios require characterization and metrology tools that characterize sidewall with essentially atomic resolution.

***Stage of Innovation Where Barrier Appears*:** R&D and production

***Measurement-Problem Part of Technical Barrier*:** Present in-line methods measure large horizontal areas and infer sidewall properties. Sidewall roughness can be measured by atomic force microscopy (AFM) and critical dimension scanning electron microscopy (CD-SEM) on today's features but not on the features that will be of the order of 10 nm in size by 2016 .

***Potential Solutions to Measurement Problem*:** Invent new methods to measure the sidewall composition and roughness of sub-22 nm features.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Spin Metrology Tools

***Submitters*:** Herbert Bennett, for industry

***Technological Innovation at Stake*:** The International Technology Roadmap for Semiconductors anticipates high-volume manufacture of integrated circuits using the 22 nanometer technology generation, which will have minimum features of ~ 10 nm by 2016. Early developers will start working on this technology within the next two years; however, metrology tools to determine properties of spins in semiconductors need to be developed so that industry may consider whether spins may replace charges as the basis for switches and transistor-like action at the end of the 2005 ITRS, that is by 2020.

***Economic Significance of Innovation*:** The Semiconductor Industry Association's economic forecast calls for 2005 sales to increase by 6.8 percent to $227.6 B, followed by increases of 7.9 percent to $245.5 B in 2006, 10.5 percent to $271.3 B in 2007, and 13.9 percent to $309.2 B in 2008. Integrated circuits with higher density increase computing speeds and reduce the costs of components for computing and a wide range of applications. If the rate of technology innovation stops or slows dramatically, there will be a slowing in the introduction of new computing and consumer electronics and this will dramatically reduce growth in the semiconductor sector.

***Technical Barrier to the Innovation*:** Lack of adequate metrology tools to characterize semiconductors, especially III-V compound semiconductors with polarized spins. Producing devices that use transport of polarized spin require new measurement methods that can detect injection of spin injection transport and decoherence of small quantities of electron spins and measure optical properties of materials used to polarize spins.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Detection and mapping of small quantities of spin-polarized electrons in spin devices and mapping properties of spin polarized materials are very difficult.

***Potential Solutions to Measurement Problem*:** Develop scanned probe methods that detect single electrons and their spins, based in part on measuring time-resolved Faraday rotation.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Semiconductor industry defect metrology tools

***Submitter*:** Kent Irwin

***Technological Innovation at Stake*:** The next generation of energy-dispersive spectrometers (EDS). The exponential rate of progress depends on continuously shrinking the minimum feature size. As the minimum feature size on integrated circuits shrinks, the size of "killer" defects and particles shrinks as well. The high yield of semiconductor processes, and thus Moore's Law, can only be maintained if metrology tools that provide non-destructive detection and simultaneous differentiation of the multiple killer defect types at high throughput are available. The standard in-line tool for the chemical analysis of defects and particles is a scanning-electron microscope (SEM) with an EDS X-ray detector. At present, these tools fail to provide fast and unambiguous analysis of nanoparticles and defects less than about 100 nm in diameter due to insufficient energy resolution to distinguish the low-energy X-ray lines. The critical defect particle size is presently 40 nm, and will reduce to 23 nm by 2010. New EDS tools are already needed by the industry today.

***Economic Significance of Innovation*:** Sales of EDS X-ray detector systems are on the order of $100 million per year, but these tools leverage the much larger semiconductor industry, which grossed about $228 billion in sales in 2005. If the semiconductor industry does not have the necessary metrology tools to control defects at smaller feature size, the impact on the industry will be significant, perhaps many billions of dollars.

***Technical Barrier to the Innovation*:** New EDS tools are already needed by the industry. The critical defect particle size is presently 40 nm and will reduce to 22 nm by 2010. As the size of critical defects and particles is reduced, the beam energy of the SEM must also be reduced to control the spot size. Low energy X-ray lines that are excited frequently overlap in a conventional EDS system. Such overlap makes it difficult to analyze the chemical composition of the particle and require the implementation of off-line, destructive, and time consuming analyses such as TEM.

***Stage of Innovation Where Barrier Appears*:** R&D and production

***Measurement-Problem Part of Technical Barrier*:** The energy resolution of conventional EDS systems are approaching the fundamental limit set by the statistics of charge carrier generation. New detector technologies are required that can measure X-ray energies more precisely.

***Potential Solutions to Measurement Problem*:** The 2005 International Technology Roadmap for Semiconductors specifies a potential solution: "Prototype microcalorimeter energy dispersive spectrometers (EDS) and superconducting tunnel junction techniques have X-ray energy resolution capable of separating overlapping peaks and providing chemical information. These advances over traditional EDS and some wavelength dispersive spectrometers can enable particle and defect analysis on SEMs located in the clean room."

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Instrumentation for Measurement of Electrical Properties at the Nanoscale

***Submitters*:** Herbert Bennett, for industry

***Technological Innovation at Stake*:** Measurements of electrical properties of nanoscale devices and structures at high and low frequencies require new instrumentation. Properties of interest include carrier mobility, resistivity, quantized conductance, and field induced mobility. The International Technology Roadmap for Semiconductors anticipates that new devices based on nanoscale properties will be needed sometime in the next 15 years.

***Economic Significance of Innovation*:** The Semiconductor Industry Association's economic forecast calls for 2005 sales to increase by 6.8 percent to $227.6 B, followed by increases of 7.9 percent to $245.5 B in 2006, 10.5 percent to $271.3 B in 2007, and 13.9 percent to $309.2 B in 2008. Introducing integrated circuits with higher density increases computing speed and reduces the cost of components for computing and a wide range of applications. If the rate of technology innovation stops or slows dramatically, there will be a slowing in the introduction of new computing and consumer electronics and this will dramatically reduce the growth in the electronic sector.

***Technical Barrier to the Innovation*:** Lack of methods for making ohmic contact with nanotubes and nanowires. Repeatable and reproducible measurements are very difficult.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Measuring and characterization with advanced nano-probe techniques electrical properties at the nanoscale are great challenges.

***Potential Solutions to Measurement Problem*:** Develop refined nano-tips for nanoprobes and advanced non-contact methods.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Software Quality and Assurance

***Submitter*:** Elizabeth Fong

***Technological Innovation at Stake*:** High integrity, safety-critical and secure software systems. Software defects and inadequate testing impact system quality, assurance, security, and performance.

***Economic Significance of Innovation*:** 35% of all successful cyber attacks result from software defects. Software over1 million Lines of Code have about 6000 defects. Annual costs from an inadequate software testing infrastructure range from $22B - $59B. Richard Pethia, CERT Director, said most software vulnerabilities come from implementation (coding) errors. Losses from the MyDoom worm were estimated at $4 billion. Enterprise software vulnerabilities will triple system downtime by 2008. Because software supports most industries (defense, health, security, etc), the potential impact to the nation's economy and security infrastructure is enormous.

***Technical Barrier to the Innovation*:** Software design defects, coding errors, and inadequate testing. Current software testing and patching solutions are inadequate. Improved software metrics and metrology are needed in development and testing to assess quality and assurance. Watts Humphreys, SEI Institute, reported that traditional, black-box functional testing will not identify security problems, since it looks at predictable user behavior, not unpredictable hacker attacks.

***Stage of Innovation Where Barrier Appears*:** Software Production, End-use.

***Measurement-Problem Part of Technical Barrier*:** Current software metrology and testing are inadequate to ascertain software assurance and trust. Applications requiring high-integrity, assurance, and security, (medical devices/systems, nuclear power plants, electrical power grid management, aircraft/ weapons control systems, homeland security, voting, etc), require improved methodologies and metrics for evaluating software trust and assurance before and after deployment.

***Potential Solutions to Measurement Problem* R&D:** Develop software assurance metrics, standards, methods, benchmarks and reference datasets to measure and test software vulnerabilities and assurance during development, and in the deployed product, to provide for a quality assurance and a certification process.

Case Study – Measurement Needs

***Technology at Issue*:** Ontology-based Interoperability

***Submitter*:** Steve Quirolgico and Steve Ray

***Technological Innovation at Stake*:** Achieving intelligent, interoperable applications and services within all major industries and domains. Ontologies describe domain-specific concepts through semantic languages that provide precise, well-defined meaning of concepts, their relationships, and properties, and that can often reference existing Web resources (e.g. vocabularies, other ontologies). Rapid cooperation and interoperability among heterogeneous and disparate applications and services requires each to "understand" the semantics and relationships of shared information without requiring human interpretation.

***Economic Significance of Innovation*:** Lack of interoperability is a major obstacle to business-to business (B2B) and enterprise application integration over the Web, resulting in inefficiency and billions of dollars in lost revenue to the American economy. Near real-time cooperation and interoperability of Web applications will have a major impact in all application domains, including e-commerce, healthcare, and defense. Semantic technologies are estimated to reduce operating cost by 20-75%, increase revenue growth 2-30 times, and increase ROI by 3-300 times over three years. Independent market analysis places the Semantic technologies marketplace at $2 billion per year, projected to grow at the rate of 40% per year through the year 2010, at which point it will be a $63 billion-dollar industry.

***Technical Barrier to the Innovation*:** Inability of software applications or services to automatically "understand" and process exchanged information. Understanding results from measuring and comparing ontological relationships, and comparing the semantics between known and new ontologies. Performing these operations is currently beyond the state-of-the-art.

***Stage of Innovation Where Barrier Appears*:** R&D, production, and end use.

***Measurement-Problem Part of Technical Barrier*:** Lack of software methods, metrics, units of measure, and tools for identifying, measuring, and "understanding" differences and similarities between known and unknown ontologies. The ability to compare and measure the degree of interoperability between two ontologies requires mechanisms that an application can use to reason about ontology semantics, attributes, contexts, and relationships.

***Potential Solutions to Measurement Problem*:** Develop methods, metrics, units of measure, and tools for relating concepts and properties between ontologies; leverage dictionaries, thesauri, and other resources; develop mechanisms that enable applications to scope and use only those parts of an ontology relevant to an application; examine various reasoning techniques for inferring interoperability (e.g., F-logic, Horn Logic, Description Logics); etc.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Fundamental Metrics for Intelligent Web Applications

***Submitter*:** John Barkley

***Technological Innovation at Stake*:** Currently, the World Wide Web consists mainly of applications that do not interoperate or share and understand information with each other. At stake is the ability to deploy intelligent business, financial, manufacturing, and other applications that interoperate and share information and knowledge. The ability of the Web to support widespread deployment of such intelligent applications is known as the "Semantic Web." The Semantic Web is shared, integrated information and knowledge between applications, and represents the major technological innovation that is at stake.

***Economic Significance of Innovation*:** The current Web fails to deliver shared, accurate information in a timely manner. While the Web has been an asset for research, it remains a chaotic, time-consuming, expensive process for industry, government, and academia to accurately and efficiently find information since it is fragmented among different resources, each of which must often be queried manually. In just one application, the capability for different healthcare organizations to share data seamlessly would result in savings of $78 billion a year. Tim Berners-Lee in his Scientific American article notes that the Semantic Web is the next killer application for the Web. It allows web applications to intelligently communicate among themselves and perform sophisticated tasks with limited human oversight.

***Technical Barrier to the Innovation*:** Barriers include methods to express and share knowledge and information meaning (e.g. ontologies, semantics, and behavior) among software applications, precise metrics and methods to measure and quantify similarities and differences in information and knowledge representations, means to determine the usability of information and knowledge representations by different applications, and means for applications to discover, exchange, and understand new information and knowledge.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The lack of precision, key metrics, e.g., expressiveness and computability, for knowledge representations. Precise usable expressiveness values for many knowledge representations are not known. For those known expressiveness values, too few have a precise usable computability value. Lack of usable expressiveness and computability values renders a knowledge representation unusable by general purpose Semantic Web methods. Access to such knowledge representations must be custom implemented at great expense.

***Potential Solutions to Measurement Problem*:** R&D to find precise conditions on knowledge representations where computability becomes practical while minimizing the effect on expressiveness. This will result in the enrichment of the metrology infrastructure enabling more expressive knowledge representations with practical computability, and that are usable with general purpose Semantic Web methods.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Trustworty Software Systems Measurement Technology

***Submitter*:** T. Rhodes

***Technological Innovation at Stake*:** Software products and systems, especially for healthcare, national defense, and safety critical applications where high-confidence and high-integrity are required to protect lives and property. U.S. industries, such as, manufacturing, transportation, and finance, also require software products whose quality, assurance, confidence, safety, reliability, maintainability, scalability and correctness be reliably engineered and highly assured to avoid or reduce economic and business losses.

***Economic Significance of Innovation*:** The cost to the U.S. economy and industry due to software problems and failures runs in the billions of dollars each year [“Why Software Fails,” IEEE Spectrum, 09/05, pp42-49]. Included are lost productivity, business, property and lives, financial loss, breakdowns of essential industrial processes and infrastructures, and disruption of health and national security services [“Software 2015: A National Software Strategy to Ensure U.S. Security and Competitiveness,” Report of the 2nd National Software Summit, April 29, 2005]. These losses will continue and grow unless better methods emerge that ensures that software quality, safety, etc., are built-in, measurable and assured during software development and deployment.

***Technical Barrier to the Innovation*:** Lack of a comprehensive, integrated development environment for engineering high quality software across the lifecycle. Unlike physical systems and engineering disciplines, software has not yet established a development framework of fundamental principals, laws, theorems, axioms, proofs, metrics, measurements, models, methods, and best practices to support the engineering of high quality, high confidence, and correct software.

***Stage of Innovation Where Barrier Appears*:** R&D, Production, & End Use

***Measurement-Problem Part of Technical Barrier*:** Current environments lack a comprehensive framework of software metrics, measurement methods, and development tools, for measuring and evaluating critical software properties and behaviors over the software life-cycle. While software metrics and tools exist, their capabilities are often limited, providing only partial solutions to ensuring correct and quality software. Further, the time and expense in using these tools often interfere with time to market and profitability of many companies, with negative consequences to the consumer and the nation from software failures and flaws. Improved software metrology is essential to resolving this dilemma.

***Potential Solutions to Measurement Problem*:** A multi-pronged approach is needed to improve software and its measurement that includes developing an engineering foundation of underlying principals, formal specifications, standard software measures and metrics, standard reference and test data, analysis and test methods and tools, analytical, statistical, and predictive models, and knowledge bases that support software engineering, measurement, and assurance throughout the software lifecycle.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue**:** Computer Modeling of Engineering Systems

Submitter**:** Ronald F. Boisvert

Technological Innovation at Stake**:** Computer models have the potential to greatly improve products and processes by allowing highly cost-effective digital exploration of design space. However, these benefits will be realized only if models and simulations are truly predictive, i.e., they provide faithful surrogates for the physical system under study.

Economic Significance of Innovation**:** Computer modeling is already heavily employed in large scale industries, such as aerospace and automotive. By allowing much more facile exploration of design space than is possible in building physical models, such techniques typically yield better designs much faster and cheaper than before. According to a 2004 report of the Council on Competitiveness, "the companies…and countries… that want to out-compete, must be able to out-compute." Unfortunately, the use of such techniques has not yet been fully embraced by many industrial sectors, such as chemical and materials, or by small to medium-scale manufacturers, who have the potential to gain significant competitive advantage from its use.

Technical Barrier to the Innovation**:** In spite of its great potential, computer modeling remains the domain of highly trained technical experts. While there are a wide variety of finite element modeling systems and tools for engineering, the range of problems that these systems can solve reliably, and the accuracy of the obtained results, remains highly variable and problem-dependent. Powerful tools in the hands of non-experts can, in fact, be dangerous. As a result, the effective use of this technology by small to medium scale industries remains largely unrealized.

Stage of Innovation Where Barrier Appears**:** R&D, End Use

Measurement-Problem Part of Technical Barrier**:** Today, the accuracy and range of applicability of computer models is rarely characterized in a serious way. Measurement of the uncertainties in computer models are needed before such tools can be used by unsophisticated users. Engineers need to know when the answers they have generated using computer modeling software are correct, or, if there is uncertainty in the results, what the level of uncertainty is.

Potential Solutions to Measurement Problem**:** While tools from the software engineering community are available to assess the adherence of a computer code to its specifications, there are few techniques and tools for assessing whether the numerical procedures, even when correctly implemented, provide an adequate solution to underlying mathematical model (verification). There are fewer tools yet to answer the even more critical question of how well the mathematical model corresponds to physical reality (validation). Development of metrics, methods, protocols, and tools for the verification and validation (V&V) of computer models are sorely needed.

Case Study – Measurement Needs

***Technology at Issue*:** XML Schema

***Submitter*:** Al Jones

***Technological Innovation at Stake*:** Interoperable Business-to-Business Information Exchange over the Internet. Manufacturers expect to use the Extensible Markup Language (XML) schema to address their interoperability problems. It will become the basis for developing all of the models that capture information that must be exchanged to conduct business and fabricate products across the entire supply chain, including Original Equipment Manufacturers (OEMs) and Small Medium Enterprises (SMEs).

***Economic Significance of Innovation*:** The inability to electronically exchange information quickly and accurately across business and manufacturing applications is indeed costly. Based on NIST-sponsored studies from the aerospace and automotive sectors, those costs are billions of dollars each year. Reducing these costs can make firms across multiple sectors and throughout the value chain much more efficient in many ways: reduced cycle times, greater capital flexibility, and increased productivity.

***Technical Barrier to the Innovation*:** Numerous software tools exist for creating XML schema, however, problems arise when applications define and use these schema to exchange data. These include: (1) Does the schema contain all required information objects, relationships, and constraints? (2) Does the schema correctly implement related existing standards, e.g., naming conventions? (4) To what extent is the schema interoperable with other, related schemas? And, (5) do applications implement the schema correctly? Methods or agreements to resolve these questions must be defined before business-to-business applications can effectively use XML to achieve interoperable data exchange over the Internet.

***Stage of Innovation Where Barrier Appears*:** Production, End-use

***Measurement-Problem Part of Technical Barrier*:** XML Schema Verification and Validation. There are three measurement aspects of these conformance-related barriers. First, there are no good definitions for what it means to be conformant. Second, there are no good ways to determine whether a given schema meets those definitions. Third, there is no agreed-upon notion of uncertainty.

***Potential Solutions to Measurement Problem*:** New standards must be developed that define conformance and set out associated metrics of conformance. R&D is needed to support this standards development process in the following ways: (1) Determination of conformance metrics; (2) Identification and/or design, development, and verification of conformance testing tools and techniques; and, (3) Development of relevant uncertainty estimation algorithms for conformance assertions.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** Embedded Software Systems Engineering and Measurement.

***Submitter*:** Al Wavering

***Technological Innovation at Stake*:** Advancement of Products and Processes that Depend on Embedded Software. The embedded software and IT component of many manufactured products and processes has become a (and often the) key driver of customer value and product differentiation, product life-cycle costs, and R&D investment and innovation. Examples include automotive operation and convenience systems, aircraft flight control systems, medical device software, pharmaceutical manufacturing control systems—and the software embedded in almost every measurement system component of the USMS itself. However, as these embedded systems become increasingly complex, manufacturers are finding it more difficult to manage the development, integration, and testing of the computing systems they depend on to introduce new capabilities and innovations in their products and processes.

***Economic Significance of Innovation*:** Currently the approaches used to develop and certify embedded software control systems rely heavily on manual methods. For safety-critical systems, any changes to system software necessitate recertification of the entire system. This results in very high costs (certification-related activities have been estimated to consume as much as 80% of the software development costs for flight control systems), and/or delayed deployment of innovations and changes that could improve performance, capability, and overall competitiveness for many different industries.

***Technical Barrier to the Innovation*:** The technical barrier to innovation is the lack of a well-developed framework of principles, methods, tools, and standards for cost-effective embedded software system engineering.

***Stage of Innovation Where Barrier Appears*:** R&D, Production, End Use

***Measurement-Problem Part of Technical Barrier*:** The measurement of system properties such as safety, reliability, functionality, stability, and security for real-time networked software-hardware control systems — and how the properties of individual components combine into overall system behavior and performance — is not well understood. Therefore manual design, review and extensive testing are the primary tools used to assess these properties, which are relatively slow and costly.

***Potential Solutions to Measurement Problem*:** Develop new ways to measure the safety, reliability, security, and other system characteristics of embedded software systems. These measurement concepts and techniques are most likely to originate from within the university or industrial research community. Software tool vendors then make these concepts and techniques available for use by manufacturers.

Case Study – Measurement Needs

***Technology at Issue*:** Healthcare Systems Integration and Interoperability

***Submitter*:** Robert Snelick

***Technological Innovation at Stake*:** Reliable and integrated communication among healthcare systems. Healthcare information systems are increasingly used to reduce costs and improve healthcare quality and safety. Market fragmentation and healthcare systems complexity preclude using a single information system to completely cover all hospitals or healthcare facilities needs. Different information systems are used, which must be coupled with each other to share data and cooperate. Integrated and reliable communications are paramount.

Economic Significance of Innovation: Integrated and interoperable information systems can improve healthcare efficiency, quality, and costs. This was a national priority in President Bush's 2006 State of the Union address; "We will make wider use of electronic records and other health information technology to help control spending and reduce dangerous medical errors." An estimated 48,000-98,000 patients die from medical errors each year. The Agency for Health Care Policy and Research reports that healthcare errors and other preventable costs amount to $17B to $29 billion each year. Part of this is due to unreliable and inadequate communication between healthcare systems. Savings from an integrated Electronic Health Record and National Health Information Network are estimated at $77.8 billon per year.

***Technical Barrier to the Innovation*:** Lack of effective standards, conformance metrics and procedures, and tools for improving interoperability of healthcare IT systems are obstacles to achieving healthcare systems integration and interoperability.

***Stage of Innovation Where Barrier Appears*:** Production, End-Use.

Measurement-Problem Part of Technical Barrier: Insufficient standards, conformance testing capabilities, measurement processes, and methodologies to validate system implementations. Systems based on common standards are more likely to interoperate. Comprehensive conformance metrics, test suites, and tools are missing for measuring standards conformance.

***Potential Solutions to Measurement Problem*:** Ensure that healthcare communication standards include conformance specifications, and provide automated testing tools and tests that can be generated dynamically and rapidly. Evaluate use of XML technologies with data exchange standards to support system integration and interoperability.

***Technology at Issue*:** Performance Standards for Ultratrace Chemical Sensors

***Submitter*:** M. Verkouteren

***Technological Innovation at Stake*:** Chemical sensors are being developed to detect vapor plumes of concealed high explosives and toxic chemicals that may be present only in the parts-per-trillion range. These sensors, which enable standoff detection, are needed for the military, homeland security, law enforcement, and first responders who currently rely on particle detection techniques requiring direct-contact, invasive, and hit-or-miss sampling methods.

***Economic Significance of Innovation*:** Reliable explosive detectors are needed to protect the public, the military, and the economic and physical infrastructure of the U.S. Towards this goal, the 2005 DHS budget $5.3 billion for aviation security and $63 million for chemical and high explosives countermeasures. The Transportation Security Improvement Act of 2005 mandates these funding levels until 2008. The DHS program includes focus on research and development of next generation technology for High Explosives Countermeasures, which will be used to develop and test field equipment, technologies and procedures to interdict suicide bombers and car and truck bombs before they can reach their intended targets.

***Technical Barrier to the Innovation*:** A quantitative, objective basis for evaluation of new ultratrace chemical sensing technology performance does not exist. Without appropriate measurements and standards capabilities, the testing for performance comparison under appropriate and controlled conditions is primarily qualitative. Although great need exists, industry lacks the capability to pursue tangible detection goals, and government agencies charged with detection of explosives are without performance criteria upon which to base verification.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Reliable mechanisms for generating standard ultratrace vapors of contraband are needed, as well as calibration and operational performance verification measurements and protocols supported by accepted quantitative standards.

***Potential Solutions to Measurement Problem*:** Improved thermodynamic data on explosive and toxic formulations would allow better quantitation of contraband, and kinetic systems such as piezoelectric nozzles could be developed for the precise generation of part-per-trillion levels of vapors from jetted droplets of standard solutions.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Mass spectrometric sensors for explosives detection

***Submitter*:** M. Verkouteren

***Technological Innovation at Stake*:** Security screeners, law enforcement, and first responders, who currently rely on manual swipe sampling methods and non-specific ion mobility detection, need reliable, high sensitivity detectors for particles of explosives. The National Research Council recently articulated the need to develop mass spectrometric (MS) techniques, which afford high chemical sensitivity and specificity, for the detection of trace explosives. A promising result has been the development of an innovative and fieldable front-end sampling method – desorption electrospray ionization (DESI) – to efficiently sample surfaces at atmospheric pressure for subsequent analysis by MS.

***Economic Significance of Innovation*:** Reliable explosive detectors are needed to protect the public, the military, and the economic and physical infrastructure of the U.S. If successfully developed, DESI-MS has the potential to double the efficiency (area/time) of sampling over swipe-based methods and at least double screening efficiency (sensitivity/false positive rate) through definitive MS identification. Also, for homeland security applications, these devices need to be cost-effective because the technology needs to be deployed widely. Better characterization can be expected to lead to cheaper detection devices as well.

***Technical Barrier to the Innovation*:** Improved understanding of charge-transfer and physicochemical interactions at surfaces interrogated by the electrospray jets are critical to advancing technological development. Improved knowledge of causes of erratic MS responses resulting from unreliable deposition of analytes onto uncharacterized heterogeneous surfaces will improve performance enhancements. Authoritative measurement standards are needed to assure the quality of trace explosive detector responses and to provide a common basis of judgment of performance capabilities.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** There is no mechanism for measuring detection limits, reliability, and false alarm rates for DESI-MS trace detection systems. No well-characterized standard surfaces exist to calibrate and verify the performance characteristics.

***Potential Solutions to Measurement Problem*:** Accurately dope a variety of surfaces of well-characterized morphology with known distributions of trace explosives. Compare performance of DESI-MS systems to spatially analyze these surfaces with targeted electrospray jets.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Firefighter Radio Communications

***Submitter*:** James R. Lawson

***Technological Innovation at Stake*:** Advanced radio systems that allow effective communication between different radio technologies, in attenuating environments, and at large incidents. Communication of verbal (audio) radio messages by emergency responders may be significantly impaired by incompatible equipment, the presence of attenuating materials, and large and/or complex emergency operations. Critical information may be lost during the communications process that may relate to life and death situations.

***Economic Significance of Innovation*:** Fires cost the US economy $219 billion and in 2004 resulted in 17,785 fire-related civilian injuries, 78,750 firefighter injuries, and 3900 deaths. Effective implementation of fire fighter locator technologies would reduce the number of injuries, fatalities, and property loss associated with fires. The failure of emergency responder communications that result from incompatible hardware, from signal absorbing or attenuating structural materials, or from overloading available communication resources, contributes significantly to the economic impact of this technology.

***Technical Barrier to the Innovation*:** There are no effective performance metrics for evaluating communications in complex scenarios. SAFECOM is developing interoperability standards to allow fire fighters from different departments to talk with each other. For instance, a radio within a system that dynamically allocates bandwidth encounters delays in the transmission of their message while the system assigns a specific portion of the bandwidth. A firefighter using an analog system does not experience this delay. If a firefighter talks during the allocation process, this delay may result in a portion of the message being lost. Interoperability standards will allow the hardware to link, but the communication may be incomplete. Structural materials attenuate radio signals, so firefighters operating in large buildings may not be able to communicate with all firefighters. There are no performance metrics to evaluate whether effective communication means linking to all, some, or one user.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Methodologies are not available for measuring the interoperability of radio communications systems, and for determining the performance of radio communications systems when challenged by signal attenuating materials and large and/or complex events.

***Potential Solutions to Measurement Problem*:** R&D to find practical ways to measure and quantify radio communication systems interoperability and effectiveness. R&D to develop new types of radio equipment and methodologies that measure the ability of radio communication systems to operate in large and/or complex environments. Coordinate the needs of the emergency responder with manufacturer R&D to produce radio systems that function in signal absorbing/attenuating structures.

Case Study – Measurement Needs

***Technology at Issue*:** Fire Fighter Locator

***Submitter*:** Nelson Bryner, Kang Lee, Leonard Miller

***Technological Innovation at Stake*:** Locating fire fighters on scene/fire ground using network of ad-hoc communication nodes, radio frequency identification (RFID) tags, or kinematic and inertial motion sensors. Locator system will allow incident commanders, both fire service and law enforcement, to track search, rescue, or fire suppression teams within structures. The current tracking system, chalkboard or hanging plastic identification tags on hooks, is unreliable and prone to user errors.

***Economic Significance of Innovation*:** Fires cost the US economy $219 billion and in 2004 resulted in 17,785 fire-related civilian injuries, and 78,750 firefighter injuries and 3900 deaths. Effective implementation of fire fighter locator technology would decrease the number of injuries and fatalities, and reduce property loss.

***Technical Barrier to the Innovation*:** Inability to characterize the performance of fire fighter locator systems on the fire ground, including high temperature, corrosive smoke, and intense thermal radiation) continues to prevent development of useable locator systems. Industry can design new RFID sensors or enhanced self-linking communication nodes, but are unable to verify the tracking capabilities of the new systems. How does one characterize the resolution? How does one verify that resolution? The lack of an effective method to assess new designs has made it difficult to understand whether new technology actually provides the necessary tracking capability for the fire service. Manufacturers cannot design better technology when they are unable to measure the performance limitations of the new technology.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The continuous tracking of fire fighters requires a scientifically based method for assessing the performance of a locator system that utilizes RFID tags, ad-hoc nodes, or kinematic sensors. Need to evaluate the spatial resolution necessary to differentiate between rooms and floors. Is the density or number of tags/nodes/sensors a function of the building configuration and construction; wide open wooden structures versus metal clad multi-roomed buildings. There are no performance standards and/or standard testing protocols for fire fighter tracking systems.

***Potential Solutions to Measurement Problem*:** Performance based metrics and testing protocols need to be developed to allow the performance of locator systems to be verified. This development should include assessing the needed characteristics such as resolution, the use of computer based models to simulate performance of new systems, and experimental test series to verify the ability of new systems to meet the needed characteristics.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue**:** Firefighter Respiratory Protection

Submitter**:** R. Bryant, K. Butler, R. Fletcher

Technological Innovation at Stake**:** Personal protective equipment with integrated aerosol detection sensors. The miniaturization of aerosol detection sensors can provide real-time warnings of exposure to hazardous environments. Unlike most workers who rely on respiratory protection equipment, first responders must work in environments where the respiratory hazards are potentially unknown. The increase in terrorist threats increases the uncertainty of potential respiratory hazards. As a result, the marketing of handheld gas and particulate sensors to the first responder community has increased. . Introducing miniature sensors capable of warning the user of hazardous exposures requiring them to check their equipment would reduce the number of respiratory injuries.

Economic Significance of Innovation**:** Using 2002 injury data from NFPA, a leading research group estimates the cost of respiratory injuries/smoke inhalation injuries at between $370 million and $490 million per year. In addition to over 1 million first responders, over 3 million U.S. workers rely on respirators of all types to protect them from worksite respiratory hazards

Technical Barrier to the Innovation**:** Respirators act as a barrier to the respiratory hazard attenuating it to acceptable levels. Measurements must be conducted inside the respirator and before entry into the body in order to quantify the protection level. In this environment, concentration levels are low and humidity levels are high. Miniaturizing aerosol detection devices with very low detection limits in the presence of interferences such as water vapor will be a challenge. In the case of first responders, the lack of a priori knowledge of the hazards creates the difficulty of choosing a measurement scheme(s) appropriate to the hazard(s).

Stage of Innovation Where Barrier Appears**:** R&D

Measurement-Problem Part of Technical Barrier**:** Miniaturized and in-situ particulate detectors tend to rely on optical scattering methods that do not condition the particulates to improve the detection limits or apply selectivity. The detection limits of these methods may not meet the required application. There is a need for enhanced information on the particle size distribution inside the respirator for various hazard scenarios. In addition, the capability to predict particle trajectory and deposition is very limited. This information is necessary for proper interpretation of measurements.

Potential Solutions to Measurement Problem**:** R&D to better characterize the measurement environment and increase the capability to monitor the environment. Explore techniques to enhance the capabilities of current measurement instrumentation and develop a new class of instruments better suited to aerosol detection.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Millimeter-Wave/Terahertz Imaging

***Submitter*:** Erich Grossman

***Technological Innovation at Stake*:** Millimeter-wave imaging systems for concealed weapon detection (CWD). Millimeter-waves are recognized to have potential for CWD due to their ability to penetrate clothing and still provide sufficient spatial resolution to identify threat objects. Non-metallic threat items are invisible to present screening systems, while X-ray backscatter systems (the chief competitor to mm-waves for this application) face major public acceptance issues due to use of ionizing radiation.

***Economic Significance of Innovation*:** Most observers believe the largest and most likely application of mm-wave imaging to be security screening, although medical and non-destructive evaluation applications are also significant. The ultimate social benefit of mm-wave imaging for CWD is in the number of public, law enforcement, and military lives saved; and in public confidence in the nation's ability to locate and to extract concealed weapons with minimal damage.

***Technical Barrier to the Innovation*:** The development and characterization of mm-wave imaging systems has been a trial and error process, primarily because of inability to accurately model and simulate the interaction of the millimeter waves with materials, objects, and collectors. Available modeling tools do not provide consistent or reliable results, hindering development and characterization of systems. Performance evaluation is presently anecdotal and could be significantly improved through the use of quantitative methods and metrics.

***Stage of Innovation Where Barrier Appears*:** Production, End-use

***Measurement-Problem Part of Technical Barrier*:** The problem is quantifying the contrast, spatial resolution, clothing penetration, and other subjective aspects of "image quality" that affect the usefulness of mm-wave imagers for this application. Presently, manufacturers and customers have very few if any quantitative measures by which to compare mm-wave imagers with each other or with the needs of the application.

***Potential Solutions to Measurement Problem*:** Develop standard objects, obscurants, scenarios, and appropriate test systems to compare measurement results to simulations, measurement results from different systems with one another, and to characterize the performance of mm-wave concealed weapon detection systems, over a range of conditions. Using either commercial imagers or custom (NIST-built) imagers, images of the standard objects etc. will be analyzed, and various quantitative measurands (modulation-transfer function, noise-equivalent temperature difference, etc.) compared.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Thermal-Imagers for Firefighters

Submitter: Francine Amon

***Technological Innovation at Stake*:** Improved infrared detectors and user interfaces/displays for firefighter thermal imagers. Thermal imagers/infrared cameras allow firefighters to see hot or warm objects and personnel through dust and smoke. Firefighters use thermal imagers to locate building occupants and downed fire-fighters. Currently, detectors and displays that are incorporated into infrared cameras perform well for many industrial applications including security or heat tracing, but do not perform well in hot, smoke-filled fire conditions experienced by firefighters. An ability to assess the performance of infrared detectors and displays will allow industry to develop better detectors and enhanced displays.

***Economic Significance of Innovation*:** Fires cost the US economy $219 billion and in 2004 resulted in 17,785 fire-related civilian injuries, and 78,750 firefighter injuries and 3900 deaths. Effective implementation of thermal imaging technology would decrease the number of injuries and fatalities, and reduce property loss. Additionally, the US market for firefighter thermal imagers is expected to grow from $81M in 2004 to $189M in 2009.

***Technical Barrier to the Innovation*:** Currently nationally recognized performance standards fail to exist against which the effectiveness of new infrared detector technology in adverse environments can be measured. Also, confusion caused by the lack of performance data and non-standard interfaces inhibits user acceptance of thermal imagers. In order for this technology to be more fully utilized, performance standards that address actual firefighting environments and uniformity of displays, off/on buttons, and temperature scales, need to be developed.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** A standardized suite of measurements are needed that quantify the displayed image resolution, contrast, uniformity, and the effects of the thermal environment on the displayed quantities. These measurements will benefit industry, which does not have performance metrics to assess the degree to which different technologies may improve thermal imager performance, and users, who currently must rely on information provided by manufacturers and/or advice from other users, both of which may be biased.

***Potential Solutions to Measurement Problem*:** Develop performance metrics to measure image quality (resolution, contrast, uniformity, and thermal-dependent system noise) that are based on scientific principles and evaluated using standardized, repeatable test methods. These measurements would function as a means to capture the strengths and weaknesses of current and next generation thermal imaging technology.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Firefighter Protective Clothing

Submitter: Bob Vettori

***Technological Innovation at Stake*:** Firefighter protective clothing fabrics that provide greater thermal protection for firefighters under low heat flux exposures. Many of the burns suffered by fire fighters occur at low heat flux exposures without apparent damage to their protective clothing. Methods do not currently exist to adequately assess the quantity of stored energy in protective clothing under low heat flux conditions. A performance metric that would characterize stored energy would lead to the development of more advanced materials, such as carbon nanotube based fabrics, and improved protective clothing designs.

***Economic Significance of Innovation*:** Fires cost the US economy $219 billion and in 2004 resulted in 17,785 fire-related civilian injuries, and 78,750 firefighter injuries and 3900 deaths. Effective implementation of protective clothing technology would decrease the number of injuries and fatalities, and reduce property loss. The most devastating of all injuries by every measure of pain, suffering, and cost is the burn injury. Burn treatment can be one of the most expensive medical procedures. The costs associated with one day in a Burn Center can approach up to $5,000.00. This does not include the substantial cost associated with plastic surgery, skin grafts, or long term rehabilitation.

***Technical Barrier to the Innovation*:** Accepted performance metrics to characterize the stored energy in fire fighter protective clothing currently fails to exist. Manufacturers cannot determine if the choice of materials for a particular design of protective clothing increases or decreases the potential for a low heat flux burn injury.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Metrics do not currently exist to measure the amount of energy stored within the protective clothing that will be transmitted to the wearer if, for example, the material is suddenly compressed against the wearer's skin. Correlations need to be developed to quantify the relationship between the energy stored in protective clothing and human tissue burns.

***Potential Solutions to Measurement Problem*:** R&D to develop techniques to measure stored energy in protective clothing and enhancement of current measurement instrumentation capabilities. An in-depth uncertainty analysis to identify individual measurement contributions to the overall uncertainty. Validate developed rating methodologies.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Advanced User Interfaces for Urban Search and Rescue (USAR) Robotics

***Submitter*:** Jean Scholtz

***Technological Innovation at Stake*:** The use of robot technology to locate victims, detect hazardous conditions, and structural issues in Urban Search and Rescue operations, allowing emergency rescue crews and civilian law enforcement first responders to send robots into potentially life-threatening environments. Robots can prove difficult to use especially in an infrequent, stressful environment that is time-critical. Having robots that have "acceptable usability" would allow FEMA task forces to purchase robots knowing that extensive training would not be required and the robots could be quickly and effectively deployed.

***Economic Significance of Innovation*:** Effective user interfaces to robotic controls can save lives of first responders by keeping them out of harms way while guiding the robots in hazardous conditions. Effective user interfaces ensure that USAR robots can save the lives of victims in their search and rescue duties. The training costs saving are significant when one considers the amount of training needed for first responders operating the USAR robots and the time away of First Responder's from their normal duties during training.

***Technical Barrier to the Innovation*:** There are currently no standards for the design of human-robot interfaces (HRI) (as there are for desktop user interfaces). "Acceptable usability" was identified as one of the top 20 requirements for USAR robots in three workshops NIST conducted with FEMA Task Forces.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Acceptable usability is a complex performance specification defined by efficiency and effectiveness measures of First Responders completing a required percentage of basic tasks using the HRI in a specified time interval. Ranges for the percentages and time need to be defined as part of the acceptance criteria for First Responder units. Measures of performance with robots depend not only on the HRI and interactions, but also on robot capabilities. It is non-trivial to develop methodologies to measure the HRI independent of the robot capabilities and to determine the baseline comparison.

***Potential Solutions to Measurement Problem*:** The solution is to develop representative tasks that stress the HRIs. These tasks can be used as baselines to measure the performance of First Responders using various robots and various HRIs.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue**:** Spectroscopic Detection of Explosives

Submitter**:** Edwin J. Heilweil

Technological Innovation at Stake**:** Detection of disguised explosive devices from a safe distance remains an overall goal for the reduction of the human toll of terrorism. Many optical methods are currently under consideration for this application due to its potential for real-time detection at many meter distances. Sub-millimeter and terahertz-wave spectroscopic approaches are currently of considerable interest because of their capability to penetrate disguising materials, e.g., clothing, plastic sheeting, etc. This capability may permit stand-off detection of bulk solid explosives delivered by suicide bombers, of improvised explosive devices (IEDs), or within containers.

Economic Significance of Innovation**:** The economic and societal impact of successful development of explosive device detection is large. Currently the DoD and the DHS are engaged in large research and development efforts to develop such technology.

Technical Barrier to the Innovation**:** Detection techniques based upon terahertz or sub-millimeter wave radiation are dependent upon the identification of spectral features of both explosive materials and potentially interfering compounds. Spectral data and libraries for these wavelengths are currently sparse, at best. Without such spectral information, discrimination between explosives and chemically similar but benign chemicals is not possible.

Stage of Innovation Where Barrier Appears**:** R&D

Measurement-Problem Part of Technical Barrier**:** Spectral data for these classes of compounds in the millimeter-wave/terahertz spectral region largely do not exist. Accurate spectral data, for both reflection and transmission, must be developed and assessed over the entire spectral range. This must be based on quantitative measurements on well-characterized materials, both explosives and other chemicals.

Potential Solutions to Measurement Problem**:** Build a comprehensive database of the complex millimeter-wave/terahertz-wave spectra of available explosive and hoax materials. Develop a millimeter-wave/terahertz-wave spectrometer and calibration standards to produce this database.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Advanced X-ray Diagnostics for Bomb Detection

***Submitter*:** Larry Hudson

***Technological Innovation at Stake*:** The needed technological innovation is the development of effective x-ray imaging systems for bomb diagnostic and disarmament applications. There are several commercial x-ray systems available to bomb technicians for use in bomb diagnostics; however, the image quality varies widely. Low-cost and inadequate systems are being purchased and deployed by emergency first responders. The technical innovation is the development and application of new standards, defined test scenarios, and new test methods focused on the technical performance of x-ray systems. This new metrology tool box, and standards that will raise the bar for vendors, will then drive technical innovation in x-ray imaging systems themselves (spatial resolution, penetration, etc.), leading to more effective bomb detection.

***Economic Significance of Innovation*:** The economic significance of the effective use of x-ray imaging systems for bomb diagnosis follows from the public, law enforcement, and military lives saved, the minimization of socioeconomic disruption, and the maintenance of public confidence in the ability of police and military to detect concealed weapons and to extract them with minimal collateral damage and casualties.

***Technical Barrier to the Innovation*:** There are no industry-wide accepted standard test methods, artifacts, or protocols for assessing and comparing the technical performance of x-ray-based bomb diagnostic systems.

***Stage of Innovation Where Barrier Appears*:** Marketplace

***Measurement-Problem Part of Technical Barrier*:** The problem involves developing standard objects, obscurants, scenarios, etc. and appropriate image-quality metrics and associated standard test methods for measuring, characterizing and comparing the technical performance of x-ray imaging systems used for bomb detection. Present methods for assessing x-ray image quality are semi-quantitative, and this has been accepted by industry. The issue will be to develop truly quantitative methods that, in the least, have a limit based on human visual performance and, better yet, that can be used in automatic recognition algorithms. The methods must be accepted by industry, which may require significant proof for this to happen.

***Potential Solutions to Measurement Problem*:** The solution requires identification of the important image quality indicators and the development of test methods, artifacts, and measurement protocols that can be used to assess imaging system performance.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Improved Visible and Infrared Vision System for Law Enforcement

***Submitter*:** Joe Rice

***Technological Innovation at Stake*:** The *Technological Innovation at Stake* is the acquisition and transfer of evidential-quality images by police departments across the nation using in-car video systems. Law enforcement is the first to respond to emergency incidents and, consequently, has the opportunity to acquire tactical information and image-based evidential data. When it comes to the question of specifying and measuring imaging quality, the International Association of Chiefs of Police (IACP) needs assistance. The new technology will enable objective image quality testing and certification that particular models of in-car cameras actually meet the IACP specifications, particularly those that relate to image quality. With this technological innovation the IACP specification can be written such that it will be much more relevant to image-based evidential data.

***Economic Significance of Innovation*:** Currently, for lack of a quantative specification coupled with lack of measurement technology to enable its verification, police departments across the country are spending millions of dollars on in-car video systems that provide unspecified and often unacceptable imaging quality that leads to unconvincing evidence. Thus, the economic significance of the NIST innovation is that it will enable more careful expenditure of precious police department dollars, reduce litigation, and increase public confidence in the law enforcement community.

***Technical Barrier to the Innovation*:** There are no reproducible performance standards for characterizing and comparing the imaging quality of visible-light imaging systems, near-infrared systems, or forward-looking infrared (FLIR) systems at the levels needed to support the specifications that the IACP is currently drafting. Therefore, no practical way exists to verify that in-car video cameras meet useful performance metrics, which has hindered development of such metrics and made it difficult for police departments to make objective procurement decisions.

***Stage of Innovation Where Barrier Appears*:** Marketplace

***Measurement-Problem Part of Technical Barrier*:** The primary issue is determining the important characteristics for a performance metric along with a physical transfer standard that can exercise the imaging systems adequately and be accepted by industry. Candidate performance metric characteristics include color, image angle and distance, lighting conditions, and moving imagery.

***Potential Solutions to Measurement Problem*:** Develop a real-time complex scene projector that can provide standardized and reproducible video images for characterizing and comparing imaging systems quantitatively. Transfer this projector technology to law enforcement standards labs, which can use it as a test bed for developing standard imaging scenes and testing performance of the imaging systems at acquiring legally viable imagery from these standard scenes.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Real-time neutron radiation monitors

***Submitter*:** David M. Gilliam

***Technological Innovation at Stake*:** Real-time fast-neutron monitors are needed both for homeland security applications and for oil-well-logging applications. Real-time neutron spectrometers are needed both as passive detectors of nuclear weapons components and as selective neutron detectors in active interrogation systems that probe cargo and baggage with some interrogating radiation to stimulate fast-neutron emission from fissile materials. Real-time fast-neutron spectrometers will improve probabilities of detection and reduce false positive rates. Current well-logging devices do not include direct real-time generator output sensors so that misleading results may occur. Innovations in real-time performance, miniaturization, robustness, and calibration these devices are needed.

***Economic Significance of Innovation*:** The economic value of improved homeland security inspection devices for baggage and cargo can be estimated by comparison of the costs of non-intrusive radiation interrogation with those of unloading/opening luggage and cargo containers for direct visual inspection. For direct visual inspection, the cost per intermodal cargo container inspected has been estimated to be about $1000, while the cost with the best fast neutron inspection technology can be expected to be about $300 per container. However, unloading and repacking containers can involve additional costs from damage to contents and difficulty with repacking into a single container. In addition, more reliable data and reduction of wasted time with malfunctioning equipment in the exploration for new oil resources could give more accurate assessments and reduce costs for the well-logging process.

***Technical Barrier to the Innovation*:** Current systems are not robust and reliable in field conditions and have time-lags of minutes to hours in giving results. Although development of neutron radiation monitoring was vigorous in the 1950's and 1960's, these efforts declined in priority after a modest stage of development was reached. Many potential technical approaches that would have been cumbersome to interpret in the past decades are now feasible to exploit with more recent developments in automated data handling.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The measurement problem is being able to do real-time spectral analysis of fast neutron radiation and absolute calibration of these detectors. Current neutron spectroscopy technology has very low detection efficiency, requiring long analysis times, and does not permit real-time spectral analysis. The current technology is too slow to be of use for inspection of cargo without seriously impeding the stream of commerce.

***Potential Solutions to Measurement Problem*:** NIST has been doing research on real-time neutron spectrometry and high-sensitivity fast-neutron detectors for several years. Development of a segmented array of ^{6}Li-loaded liquid scintillators appears to be a feasible solution, but a great deal of system integration development remains to be done.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Soft Body Armor

***Submitter*:** S.D. Ridder

***Technological Innovation at Stake*:** Bullet-resistant soft body armor currently in use has been credited with saving more than 2500 lives, however, the introduction of new ammunition threats such as frangible bullets and the environmental degradation of the ballistic-resistant fibers used in the body armor has compromised the reliability of these systems. The National Institute of Justice (NIJ) Standard-0101.04, "Ballistic Resistance of Personal Body Armor" is currently undergoing revision and will benefit from measurements and modeling of the high strain rate mechanical properties and deformation behavior of frangible bullets and the response of ballistic-resistant fabric systems to bullet fragments and environmental damage.

***Economic Significance of Innovation*:** A major U.S. supplier stopped production of soft body armor products with Zylon fibers and recommended that all soft body armor with Zylon fibers now in use be removed from service as soon as replacements are available due to concerns with the reliability of environmentally aged Zylon fibers. This announcement and subsequent law suits have forced the company into a bankruptcy reorganization. Performance properties of ballistic fabrics are needed to help avoid these product recalls and the economic damages that they cause.

***Technical Barrier to the Innovation*:** Mechanical properties and deformation behavior of materials undergoing rapid rate stress and strain are needed to improve performance standards used by manufacturers in the design and testing of soft body armor systems.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** Ballistic performance of frangible bullets and soft body armor materials requires mechanical property measurements at strain rates $\approx 10^3\ s^{-1}$. Measurement of the mechanical properties of ballistic fabric materials is complicated by numerous environmental degradation effects and statistical variations in virgin fibers. Methods for making high quality measurements of relevant material properties at these high strain rates are not well established, and instruments normally used for materials properties at these high strain rates are not well established, and instruments normally used for materials properties measurement are either limited in strain rate or absolute strain. There are no open-source models available to body armor developers for this purpose.

***Potential Solutions to Measurement Problem*:** R&D is needed to measure mechanical performance and deformation behavior of frangible bullet materials and ballistic fabrics under strain rates $\approx 10^3\ s^{-1}$. Data from these tests incorporated in validated finite element models of bullets impacting ballistic fabrics would provide the design tools needed for NIJ to write improved performance standards. These standards and models would provide manufacturers of soft body armor the necessary design requirements.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Minimally invasive in vivo optical tissue diagnostics

***Submitter*:** P. Williams, S. Dyer, T. Dennis

***Technological Innovation at Stake*:** Two innovations to Optical Coherence Tomography (OCT) will allow broad application in medical diagnostics: increased measurement speed (image quality, screening costs, and patient comfort depend on rapid scans) and better measurement validation (enables technology-invariance and instrument interoperability).These innovations will change OCT, a young biomedical imaging technique, into a widely-applicable, quantitative measurement tool for absolute assessment of tissue health. OCT optically probes tissue in a way similar to ultrasound but with 10-100x better spatial resolution.

***Economic Significance of Innovation*:** Cancer and heart disease account for 40% of deaths in the U.S. This year, over 700,000 Americans will have a heart attack caused by ruptured arterial plaques. OCT promises to reduce this number by identifying which plaques are vulnerable to rupture. Early cancer screening is key to survival. Studies show that routine screening yields up to a 60% reduction in death rate for colorectal and cervical cancers (compared with no screening). OCT's potential for "optical biopsy" offers to make cancer screening less invasive, more effective, and more widely used for early screening, saving lives and reducing the $70B annual expenditure on cancer's medical costs.

***Technical Barrier to the Innovation*:** Measurement speed is limited by a lack of rapidly tuning low-noise lasers and broad-band light sources, high-sensitivity detectors, cost-effective near-IR detector arrays, and by measurement noise in general. Measurement validation is limited by the current OCT accuracy assessments, availability of comparable techniques, well-characterized and stable phantoms, and an incomplete data bank of optical tissue properties (refractive index, scattering and absorption parameters).

***Stage of Innovation Where Barrier Appears*:** R&D barriers limit OCT's full clinical potential

***Measurement-Problem Part of Technical Barrier*:** Fast-tuning lasers need high-speed wavelength metrology at 850 and 1300 nm. Broadband light sources need measurement protocols for noise and spectral ripple. OCT functionality needs low-noise, low-uncertainty measurements of fluorescence spectra, refractive index, dispersion, and birefringence. Measurement validation needs OCT measurement uncertainties, stable phantoms, and measurement comparisons between instruments. Optical diagnostic and therapeutic tools (not just OCT) need an accurate data bank of the optical properties of human tissue.

***Potential Solutions to Measurement Problem*:** R&D to develop needed components, design and test new OCT techniques, develop measurement validation techniques and phantoms. Multi-level comparisons of accuracy and efficacy will be needed. Optical tissue data measurement needs must be prioritized, coordinated, and carried out.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Next Generation High Resolution Magnetic Resonance Imaging (MRI) Systems

***Submitter*:** Stephen Russek

***Technological Innovation at Stake*:** More advanced MRI modalities will measure new physical properties and functionalities such as blood oxygen content and neural connectivity. These innovations for MRI will enable more accurate and consistent interpretation of images, allow better monitoring of MRI system stability, assist in the establishment of better protocols for intersystem image comparability, and provide a quantitative basis for validating new imaging modalities. Each of these innovations would contribute to better diagnoses, enabling more efficient treatment of cancer, cardiac disease, and brain disorders. Quantitative MRI standards will assist in the development of innovative new MRI modalities that are attempting to measure new physical properties

***Economic Significance of Innovation*:** At present the MRI industry in the U.S. is $30 billion/yr, however, the economic impact of MRI goes far beyond the value of the organizations that provide equipment, service providers, and radiologists. The larger secondary economic impact includes improved diagnoses, more efficient drug and therapy development and the associated improved quality of life to patients. The availability of quantitative standards will contribute to maximizing this secondary economic impact by providing more accurate and consistent imaging that can be more reliably and reproducibly linked and validated with disease mechanisms and therapeutic outcomes. Quantitative standards will facilitate the upcoming transition to quantitative imaging that will enable faster and simpler interpretations of images.

***Technical Barrier to the Innovation*:** The development of quantitative MRI standards is necessary for the development of this next generation MRI system. Developing these standards will require research to clearly define the physical properties that are measured in MRI and to establish reference samples with stable properties.

***Stage of Innovation Where Barrier Appears*: R&D,** End Use

***Measurement-Problem Part of Technical Barrier*:** Accurate measurements and traceability are underlying requirements for MRI standards. Dedicated measurement systems will need to be developed to design, validate, and maintain standards. New measurements will be required such as precise determination of flow fields and anisotropic diffusion dynamics in biological artifacts.

***Potential Solutions to Measurement Problem*:** A working group that includes hospitals, universities, and biomedical companies, along with appropriate input from regulatory agencies could establish guidelines for required standards. Once standards and protocols are developed they can be transferred to biomedical phantom manufacturers for distribution. NIH or NIST will need to retain primary standards and provide traceability for the secondary standards distributed by the phantom manufactures.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Nanomagnetic MRI Contrast Agents

***Submitter*:** Stephen Russek

***Technological Innovation at Stake*:** Engineering new types of contrast agents, understanding the nano-scale interactions of contrast agents with nuclear spins in biological systems, improving resolution to single-particle sensitivity, and measuring the functionalization and activation properties of the contrast agents are the key technical challenges. New classes of nanomagnetic contrast agents are being developed to dramatically extend the imaging modalities of magnetic resonance imaging (MRI). Contrast agents are being developed that target specific tissues, metabolic pathways, neural and cardiac functionalities. These new contrast agents will enable new types of imaging of molecular and neural activity and provide better diagnoses for a broad class of medical problems.

***Economic Significance of Innovation*:** More than 25 million patients in the U.S. undergo MRIs each year. Doctors use contrast agents in about 30 percent of MRIs. Contrast agents increase the sensitivity and specificity of the scans, making it easier for doctors to deliver a diagnosis. The enhancement of the imaging and diagnostic capabilities that will result from the use of new contrast agents is expected to significantly increase the size of this industry, and expand early diagnostic capabilities for cancer, pathological brain structures (tumors, inflammation, ischemia), hepatic lesion detection and vascular visualization. Ultimately, future agents may allow visualization of therapeutic drug delivery for closer and earlier efficacy monitoring. The size of the MRI contrast agent market itself is expected to grow to several billion dollars per year. However, the economic impact through improved diagnoses and earlier treatment will be far larger.

***Technical Barrier to the Innovation*:** The technical barriers to the development of better contrast agents are the ability to nano-engineer contrast agents that have high spin relaxivity, are non-toxic, and can be targeted to the desired organ or tissue. New types of contrast mechanisms must be developed to increase the sensitivity to enable imaging of individual contrast agents and their targets.

***Stage of Innovation Where Barrier Appears*:** R&D, End Use

***Measurement-Problem Part of Technical Barrier*:** New types of measurement tools are required to understand the detailed magnetic interaction of the contrast agents with nuclear spins in biological systems. New metrology is needed to understand how the functionalization of the contrast agents affects relaxivity properties. New metrology is required to understand and develop single particle tracking with MRI systems.

***Potential Solutions to Measurement Problem*:** A coordinated effort is required between pharmaceutical companies, NIH funded research institutions, and metrology labs to develop the basic knowledge and metrology infrastructure required for more innovative and efficient development of contrast agents.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue**:** Quantitative Imaging for Tissue-Engineered Medical Products (TEMPS)

Submitter**:** Marcus Cicerone

Technological Innovation at Stake**:** The creation of man-made tissues or organs through tissue-engineered medical products (TEMPs), constitutes an exciting, relatively new strategy that has potential to revolutionize the medical treatment of many injury and disease states. Approaches range from enhancing re-growth of tissue to stimulating re-growth of an entire organ. In most cases, biodegradable polymers are used as a scaffolding to guide tissue and organ regeneration.

Economic Significance of Innovation**:** It is expected that the potential economic impact of the Tissue Engineering field will be very large. Diabetes mellitus, a primary target condition, has estimated annual direct and indirect costs of nearly $120 billion -including secondary illnesses. This accounts for more than 10 percent of the nation's total annual healthcare costs. In the cardiovascular arena, the ability to regenerate heart muscle or provide tissue engineered blood vessels will save billions and significantly increase quality of life while reducing morbidity and mortality rates. The NIST ATP program estimates that tissue-engineered livers alone could save more than $140 million / year assisting chronic and acute liver failure patients. Tissue-engineered articular cartilage will limit knee replacements for thousands in the U.S., improving worker productivity and increasing quality of life.

Technical Barrier to the Innovation**:** Both manufacturers and regulatory agencies are often uncertain as to how to quantify performance and specifications of TEMPs, and managing in-vivo monitoring effectively.

Stage of Innovation Where Barrier Appears**:** R&D

Measurement-Problem Part of Technical Barrier**:** An adequate measurement infrastructure does not exist for this industry because it is still in its infancy. This impacts research, manufacturing, and regulatory issues, and must be rectified. A recent FDA Critical Path document concisely stated the problem: “Additional characterization procedures and standards for …other cellular products, bioengineered tissues, and implanted drug-device combinations …are urgently needed.”

Potential Solutions to Measurement Problem**:** International standards organizations, including ASTM and VAMAS recognize the need for standards and reference methods for TEMPs. They have recognized that this can be best accomplished by development of **non-invasive, quantitative imaging methodologies,** which can be used as bases for standard protocols, and with which products can be non-destructively evaluated in comparison to reference artifacts and benchmarks before and after placement.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Radio-diagnostic Molecular Imaging (Positron Emission Tomography - PET)

***Submitter*:** M. Schultz

***Technological Innovation at Stake*:** Use of radionuclide-based imaging for diagnosing and locating pathogenic (i.e., cancerous) tissue has increased dramatically, while methods for validating accuracy of the dose assessment have not. PET and PET/CT combine radionuclides with nano-engineered targeting delivery molecules to image both structure and function of pathogenic tissue/organs to provide a new approach to imaging of malignant tissues.

***Economic Significance of Innovation*:** Advances in PET scan technology can improve early diagnosis of breast cancer, lung cancer, heart disease, and brain disorders. Demand for PET increased by 35% in 2004, to about 900,000 procedures. By 2010, PET volume may rise to 2.1 million procedures. PET/CT reimbursements average about $2K per procedure ($4B total expected in 2010), due to the number of therapeutic procedures increasingly combined with molecular imaging procedures for treatment planning. By 2008, therapeutic sales may exceed $3 billion. The cost of using radio-therapeutics includes the amount of radioactivity purchased (more activity is higher cost). However, the window of "safe and effective" dose of radio-therapeutics is typically narrow (e.g. 10%). Improved accuracy in diagnostics using PET/CT imaging would improve safety of treatment plans through lower doses, reduce cost required for radio-therapeutics, and improve efficacy resulting in fewer treatments through greater precision.

***Technical Barrier to the Innovation*:** (1) lack of physical/mathematical anthropomorphic radioactivity standards – human body surrogates to serve as sources for acquisition of standard images; (2) inadequate image quality standards for qualifying image attributes (e.g., scaling factor algorithms) for assessing organ and cellular uptake; and (3) lack of technical interoperability standards for ensuring standard image rendering, storage and retrieval of image data. No national physical-anthropomorphic standards. Technical and semantic standards exist for hardware and software, but no test bed facilities exist to evaluate effectiveness and accuracy, precision, and reproducibility of image rendering and interpretation.

***Stage of Innovation Where Barrier Appears*:** End Use

***Measurement-Problem Part of Technical Barrier*:** The accurate determination and characterization of radioactivity in a volume are to model patient distribution for image interpretation are needed in treatment planning. There is a lack of standards and test bed facilities suitable for performance testing of technologies employed.

***Potential Solutions to Measurement Problem*:** (1) <u>Phantoms</u>: Develop standard-physical and mathematical anthropomorphic radioactivity phantoms for test bed facilities to assess accuracy and precision of imaging technologies, and interpretation of images. Develop mathematical models that would allow extension of phantom-test-bed experimental results to the continuum of human physiology is required. (2) <u>Image Quality</u>: Develop/validate image quality standards and create image quality (accuracy, precision) National test-bed to test image rendering and interpretation. (3) <u>Interoperability:</u> Develop/validate standards for imaging [syntax/grammar in technical (architecture) and semantic (protocols, data objects, codes)] areas. Create industry-based infrastructure for use-case testing of PET/CT imaging devices. Develop a National test facility to serve interoperability testing needs and device certification.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Polarized ^{3}He gas for advanced medical imaging

***Submitter*:** Tom Gentile

***Technological Innovation at Stake*:** Polarized gas magnetic resonance imaging is currently emerging as a method for evaluating lung disease. In this method, ^{3}He or ^{129}Xe gas is spin-polarized by optical methods and inhaled, allowing direct imaging of lung airspaces, which is not possible with conventional MRI. Because the gas polarization is not dependent on the strength of the magnetic field, such imaging could be performed in very low field MRI devices. After decades of research, the maximum polarization of ^{3}He gas achievable by the spin-exchange optical pumping (SEOP) method appears limited to 75%. Achieving 100% polarization would have a notable impact on several applications, particularly in medical imaging.

***Economic Significance of Innovation*:** Polarized gas magnetic resonance imaging is currently emerging as a method for evaluating lung disease, in particular chronic obstructive pulmonary disease, which is the 4th leading cause of death in the U.S. Widespread acceptance and use of polarized gas MRI could lead to routine screening of all patients who are smokers or previous smokers (6% of the population) resulting in early detection and better disease management which can significantly lower health costsSince ^{3}He gas does not occur naturally (it is obtained as a byproduct of nuclear weapons production) and the world's supply is limited, the most efficient use of this gas is necessary. ^{3}He MRI may also have a positive impact on the management and treatment of chronic sinusitis. Sinusitis is a significant health problem in the U.S., affecting 33 million Americans and resulting in 22-25 million physician visits annually with medical costs estimated at more than $ 5.8 billion yearly.

***Technical Barrier to the Innovation*:** It has been determined that the polarization achievable via SEOP is limited by a previously unrecognized temperature-dependent form of nuclear spin relaxation. However, the origin of this relaxation is unknown. Currently there is no NIST-traceable method for measuring the "dose", i.e. the degree of polarization of the gas.

***Stage of Innovation Where Barrier Appears*:** R&D (1st), Production (2nd)

***Measurement-Problem Part of Technical Barrier*:** Careful measurements and innovative methods are required to understand the current limit on polarization. Accurate measurements of the ^{3}He polarization are required and a method is needed for measurement traceability. Because different techniques exist for polarization measurement, the field will benefit from a comparison of these methods.

***Potential Solutions to Measurement Problem*:** Neutron-based measurements, performed at the NIST Center for Neutron Research, provide an accurate method for determining ^{3}He polarization. This capability could be employed to compare with other methods such as electron paramagnetic resonance and for calibration of nuclear magnetic resonance instruments that measure polarization. Comparison of certain spin-relaxation data in ^{3}He and ^{4}He, SEOP measurements with a series of alkali metals, and a careful series of relaxation measurements vs. temp. can help determine the cause of the current polarization limit.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue**:** Quantitative Optical Medical Imaging

Submitter**:** G. Fraser

Technological Innovation at Stake**:** Effective optical imaging methods at the micro to macro spatial scales will provide clinicians with new approaches to improve diagnosis, assess treatment efficacy, and guide surgical procedures. Wide acceptance of quantitative optical imaging methods would also improve the objectivity of many medical decisions often based upon subjective assessments of tissue color and appearance, potentially reducing the need for highly trained specialists and providing an objective and defensible method for diagnosis and treatment decisions.

Economic Significance of Innovation**:** Effective optical imaging methods at the micro to macro spatial scales will provide clinicians with new approaches to improve diagnosis, assess treatment efficacy, and guide surgical procedures. Wide acceptance of quantitative optical imaging methods would also improve the objectivity of many medical decisions often based upon subjective assessments of tissue color and appearance, potentially reducing the need for highly trained specialists and providing an objective and defensible method for diagnosis and treatment decisions.

Technical Barrier to the Innovation**:** Tissue opacity in the visible and thermal infrared limits the application of optical imaging methods at these wavelengths to tissue surface measurements either of the skin or of internal surfaces through endoscopic or laparoscopic procedures. In the near infrared, tissue transparency increases, however, optical scattering from the inhomogeneous turbid medium has limited the utility of this wavelength region. The recent introduction of optical coherence tomography (OCT) in optometry demonstrates the potential for optical imaging methods in medicine. Technical barriers include a lack of understanding of the optical properties of tissues and its variation with disease. Also lacking is a quantitative understanding of light propagation in tissue in the near infrared.

Stage of Innovation Where Barrier Appears**:** R&D

Measurement-Problem Part of Technical Barrier**:** The successful development of new optical imaging methods require quantitative tissue optical models and measurements, tissue phantoms (tissue mimetics perhaps based on polymers with realistic optical properties to serve as standards), improved tomographic inversion algorithms, compact optical instruments integrated with endoscopes and laparacopes, rapid spatial, spectral and angular measurement instruments appropriate for the clinical or surgical environment, multispectral methods, and approaches to fuse optical images with images from magnetic resonance imaging (MRI), positron emission tomography (PET), or other imaging modalities.

Potential Solutions to Measurement Problem**:** Improved optical models, tissue standards, normal and diseased tissue optical properties databases, and successful clinical demonstrations.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Medical imagery as a biomarker for disease extent and change measurement

Submitter**:** Charles Fenimore

Technological Innovation at Stake: Development of reliable computer-assisted diagnosis of medical imaging as a biomarker for disease progression. Software tools should not be a source of uncertainty in assessment of drug therapy or disease progression, by imaging or other biosensor data sources. Current change analysis software tools are inadequate for this task. Initial needs are for application to computed tomography applied to lung cancer, but will extend to other imaging techniques such as PET-CT, MRI, and Optical Imaging.

Economic Significance of Innovation**:** A key application will be in drug development. The cost of developing a new drug exceeds $800 million and only one in five drug candidates that enter clinical trials gets approved. Reliable metrology and standards for assessment of drug response would both lower these costs and limit the significant number of failed drugs in clinical trials by identifying the efficacy and safety profile of the drug candidate earlier in the process. There is evidence that the clinical use of standardized software tools can result in improved diagnosis, thus improving health, increasing productivity, and lowering the 15% of GDP spent on the nation's health care. In addition, computer reading improves the productivity of interpreting the large and growing volumetric medical imaging from PET, CT, and MRI. This is significant in view of the disparity between the relatively constant number of radiologists and the rapidly growing volume of imagery. As a consequence, it is predicted that in a decade most primary medical imaging reads will be done by computer (Dr. Laurence Clarke, NCI).

Technical Barrier to the Innovation**:** The problem arises at the confluence of advanced medical imaging equipment and computed image analysis. Medical imagery, such as CT scan, is valuable for identifying disease, but quantifying disease extent and change over time from therapies (days versus current ability of weeks or months) is subject to high levels of uncertainty. High levels of uncertainty over shorter time spans (days) and the lack of standards limits the application of computer assisted medical imaging in drug development protocols and in clinical settings.

Stage of Innovation Where Barrier Appears**:** R & D

Measurement-Problem Part of Technical Barrier: There is a need for development of methodology and metrics for (1) quantifying disease extent and change, for example measurement of volume and (2) assessment of software-assist tools for bio-imaging.

Potential Solutions to Measurement Problem: Develop large number of well-characterized medical image datasets with radiologists' annotations. Develop assessment/benchmarking methodology for software tools. Standard performance measures are expected to lead to improved tools.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Biomedical Imaging as a biomarker for Change Measurement in Therapy

***Submitter*:** Ram Sriram

***Technological Innovation at Stake*:** The creation of standards for image data collection and analysis as applied to imaging as a biomarker for drug response will permit the following innovations in a more timely manner: 1) more quantitative methods for staging of disease; 2) improved metrics for drug response, reducing the size of drug trials submitted to the FDA by pharma; and 3) facilitate earlier "go and no go" decisions for different therapy treatment methods, thus reducing the cost of drug development.

***Economic Significance of Innovation*:** The cost of developing a new drug exceeds $800 million and only one in five drug candidates that enter clinical trials is approved. Biomedical imaging is currently playing an increasing role in clinical trials. Change measurement of images is a critical aspect of this process and must be addressed accordingly. In vivo imaging and molecular imaging, in particular, will permit measurement of early response to therapy, providing significant cost savings in drug trials required for new therapeutics in the U.S.

***Technical Barrier to the Innovation*:** 1) lack of standards for data collection across and array of different imaging platforms; 2) lack of robust methods for measurement of change using biomedical imaging, through the entire data collection to data analysis chaining; 3) inadequate image quality standards for qualifying image attributes for measuring change; and 4) lack of technical interoperability standards for ensuring standard image rendering, storage and retrieval of image data. Technical and semantic standards exist for hardware and software, but no test bed facilities exist to evaluate effectiveness and accuracy, precision, and reproducibility of image rendering and interpretation.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The ability to accurately determine and characterize change using images over short times, days versus weeks or months, and the lack of standards and test bed facility to establish traceability.

***Potential Solutions to Measurement Problem*:** Image Acquisition: Capture consistent and high quality images during the course of therapy through the entire drug life cycle, 2) Image Analysis: Develop standardized performance measures for software; 3) Interoperability: Develop/validate standards for imaging (syntax/grammar in technical architecture and semantic protocols, data objects, codes); 4) Testing: create industry-based infrastructure for use-case testing of various biomedical imaging devices, and create a national test facility to test imaging rendering and interpretation and serve interoperability testing needs and device certification; and 5) Image data management: Develop standard archival and access methods to image storage and retrieval.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Integrated Circuit Photomask Metrology

***Submitter*:** James Potzick

***Technological Innovation at Stake*:** Integrated circuit photomask technology is an enabler for the worldwide electronic products economic engine. Photomasks face new challenges in maintaining the vigor of this engine, in the form of innovative resolution enhancement features like sub-resolution scattering bars, Optical Proximity Correction (OPC) serifs, and phase shifters. Overcoming these challenges will enable the continued progression of Moore's law and the economic benefits that follow.

***Economic Significance of Innovation*:** The functional density of integrated circuits has been growing exponentially for over 25 years (see Moore's Law) with the cost per function in consumer products declining commensurately. This exponential growth has created one of the largest market segments of the world economy and improved the worldwide standard of living. The market, however, has discounted this historical growth, so that any slippage below the Moore's law curve is perceived as a decline. Should the cost per function of consumer electronic products level off or increase within a relatively short time span, the potential for an economic worldwide depression may be realized.

***Technical Barrier to the Innovation*:** Improved accuracy optical imaging models are needed in order to specify mask features that will achieve the desired effect on the wafer during exposure. The sizes and placement of these features on the mask must be measured accurately in order to manufacture a photomask to its specifications. A misplacement of a subresolution scatter bar by a few nanometers can render a $100,000 photomask marginal in its performance, resulting in the loss of perhaps millions of dollars in wafer product. There is no optical limit to the smallest feature size on a wafer; instead the process becomes more dependent on control of process parameters like feature size and placement on the photomask, focus, dose, illumination parameters, etc. Thus, smaller features do not become impossible at some point, they just gradually become more difficult and expensive.

***Stage of Innovation Where Barrier Appears*:** R&D and Production

***Measurement-Problem Part of Technical Barrier*:** The tolerances of photomask resolution enhancement features and the uncertainties of their measurements combine to establish the probability that the mask will perform as intended. As the cost per unit area of making integrated circuit chips rises exponentially with diminishing feature sizes, this probability can be maximized only through research.

***Potential Solutions to Measurement Problem*:** Verify and improve the performance of existing optical imaging models. Improve photomask feature measurement techniques. Quantify the effect of measurement uncertainty on mask performance.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Magnetic Data Storage

***Submitter*:** Theodore Vorburger

***Technological Innovation at Stake*:** The continued miniaturization of recording density in the magnetic data storage industry relies on decreasing the spacing between the magnetic head and the storage medium. Improved speed and compactness of magnetic data storage devices comprises one of the innovation drivers of the successful and hugely important microelectronics industry

***Economic Significance of Innovation*:** The push for large hard disk drive (HDD) storage capabilities on desktop computers and small portable products, such as, cell phones, PDAs, digital still cameras, and digital video cameras, could increase the HDD market from 372.2 million units in 2005 to 408.3 million units in 2006, according to a recent report of The Information Network (TIN). The HDD market is expected to grow from $3.3 billion in 2005 to $4.5 billion US in 2009 according to Gartner Dataquest. By meeting the roadmap, HDD's will satisfy anticipated multimedia library storage demands in micro and mobile devices. If the speed and compactness of magnetic storage does not continue to improve, then the development of improved products, such as computers, that use magnetic storage devices is hampered, and the vitality of the industries that provide those products is compromised.

***Technical Barrier to the Innovation*:** Decreasing the spacing between the magnetic head and the disk medium means decreasing the flying height of the slider with respect to the medium. However, both the head-medium spacing and the flying height become relatively more uncertain as the spacing decreases. The clearance between slider and medium is a problematical "width" dimension whose value also depends on the diamond like coating on the head and the lubricant coating on the medium. As the head-medium spacing decreases from 20 nm in 2003 to a projected 2.8 nm in 2013, industry may be able to make relative measurements of the various spacings and do this in a dynamic way, but the industry has called on NIST to provide calibrations for its measurements in order to determine the function of its storage technologies more accurately.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** In the 2005 Information Storage Industry Consortium (INSIC)-NIST Metrology Workshop held on October 20-21, 2005, the industry cited as its highest priority in the Head Disk Interface area an optical fly height measurement standard, which would simulate high density disk fly height conditions and materials that must fit existing fly-height testers. This would be a tapered air gap with a thin end of 2 nm to 5 nm and a thick end of 50 nm to 200 nm. There is currently no such available reference standard for hard disk drive (HDD) fly height measurement. This formal measurement need arising from a USMS Workshop echoes requests previously made directly to NIST by representatives of the Zygo Corporation. Zygo is a metrology supplier to this industry.

***Potential Solutions to Measurement Problem*:** A transparent glass package with a tapered gap calibrated by phase shifting interferometry and refractometry.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Integrated Circuit Optical Linewidth Metrology

***Submitter*:** Rick Silver

***Technological Innovation at Stake*:** Measuring feature linewidth directly on a wafer at different photolithographic levels in the manufacturing integrated circuits is an enabling technology for the worldwide electronic products economic market. As the critical dimensions of key attributes in semiconductor devices get smaller and smaller, measuring the sizes of these features is becoming increasingly difficult with new challenges in maintaining the accuracy requirements and the basic ability to even resolve the features.

***Economic Significance of Innovation*:** The US semiconductor industry has held a preeminent position in the design of advanced and next generation semiconductor devices as well as the instrumentation used to manufacture them. For US industry to maintain a leadership role in the continued exponential shrinkage and production of semiconductors with yet lower cost per function, significant investment and R & D in manufacturing metrology is required. This exponential growth has created very significant market segments with technological leadership from the US. Even the smallest improvements in measurement innovation and manufacturing process control can yield millions of dollars in return. This economic sector is so advanced and automated that clever solutions and advances can have very significant and measurable effects on profit levels. The techniques suggested for development would enable closed loop, high through-put metrology improving yield which is becoming a requirement at this level. High through-put non-destructive metrology capable of measuring 10 nm sized features with sub-nm accuracy would enable improved manufacturing as required by the ITRS roadmap.

***Technical Barrier to the Innovation*:** Accurate optical measurement techniques, optical hardware alignment and electromagnetic scattering models which simulate the imaging process are needed to accurately and provide robust measurement and process control capabilities. The dimensions of features on the wafer must be measured accurately in order to obtain acceptable manufacturing yields, device performance, and profit levels. An improvement in linewidth process control or measurement of only a single nanometer can result in millions of dollars in increased profits.

***Stage of Innovation Where Barrier Appears*:** R&D and Production

***Measurement-Problem Part of Technical Barrier*:** There are several challenges in measuring optical targets composed of features nearly $1/10^{th}$ the size of the measurement wavelength used. Aligning the optics, defining algorithms and CCD measurement capabilities with better than 1 nm resolution and accuracy is very challenging. Accomplishing this in a way which enables high throughput and accuracy requires pushing optical techniques to new, advanced levels. Current CCD metrology is limited by target sizes to 20 microns for scatterometry and electron microscopes have a host of challenges at this level. Overlay tools cannot measure or image features the sizes coming in manufacturing. The ability to measure 10 nm sized features with placement accuracy of 0.1 nm is not currently attainable.

***Potential Solutions to Measurement Problem*:** Implement new high resolution scatterfield microscopy techniques to the critical dimension wafer measurements. Quantify the effect of measurement uncertainty on device yield and process control.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** SEM and AFM Modeling for Semiconductor Electronics and Nanotechnology

***Submitter*:** John Villarrubia

***Technological Innovation at Stake*:** "Small" is often the essence in semiconductor electronics and emerging nanotechnology areas. In semiconductor electronics the state of the technology at a given time is customarily summarized by a single metric—the size of the "critical dimension" (the smallest feature size). Microprocessor speed and memory density depend directly upon the critical dimension. Inability to control (maintain reproducibility of) critical feature sizes is equivalent to inability to control essential properties of the product. Such process control is normally accomplished using a <manufacture> – <measure the result> – <determine manufacturing error> – <adjust inputs to correct errors> feedback loop. Measurement is an essential component of this control loop. The ability to manufacture products using feedback to maintain reproducible feature sizes is constrained by our ability (or lack thereof) to accurately measure those sizes.

***Economic Significance of Innovation*:** In semiconductor electronics smaller critical dimensions have demonstrable economic value. Higher density memory and faster microprocessors have greater value (and sell for a higher price) than their lower density or slower competition. Estimates have been made that each nanometer of reduction in transistor gate width produces a speed increase worth several billion dollars to the microprocessor segment of the economy alone. The value in less well established industries like the emerging nanotechnology industry are more difficult to quantify, but the potential for large economic value is widely recognized, as evidenced in well publicized government and private sector investments in this area.

***Technical Barrier to the Innovation*:** The ability to fabricate, manipulate, and see features at these small size scales are all new and challenging tasks. Image artifacts are at the same size scale as the needed accuracy. Modeling is needed to extract specimen geometric information from the AFM or SEM image. Models often do not exist. In cases where they do, accuracy has been demonstrated only for a very restricted set of materials and feature types.

***Stage of Innovation Where Barrier Appears*:** R&D + Production

***Measurement-Problem Part of Technical Barrier*:** All microscopes have finite spatial resolution, set by the scale of the physical interaction between the microscope's probe and the sample. In an optical microscope the scale is set by the illumination wavelength. In an electron microscope it is generally set by the beam size and/or size of scattering volume. For existing microscope technologies, sub-micrometer (for light) or sub-10 nm (for scanning electron microscopes) are easily achievable. While more than adequate for macroscopic technologies, these scales are comparable to feature sizes for nanotechnologies and therefore not adequate

***Potential Solutions to Measurement Problem*:** (1) New microscopies with higher spatial resolution, (2) better use of existing resolution through models that allow correction of measurement artifacts and thereby correct interpretation of images, and/or (3) standard samples of known shape, size, and composition that permit experimental determination of measurement artifacts.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Scanning Electron Microscope Nanocharacterization

***Submitter*:** Michael Postek

***Technological Innovation at Stake*:** Nanocharacterization spans issues in physical and chemical metrology including force and length measurements, chemical composition determination, shapes of pores and particles, and 3D relationships of complex nanoscale components. The current state of the art might best be viewed as a multidimensional parameter space in which trade-offs are made between spatial resolution and sensitivity, chemical speciation and sampling volume, and speed of data acquisition and detection limits. Nanocharacterization will not be sufficient if these trade-offs continue to be necessary--to support the emerging nanotechnology industry, advances in SEM nanocharacterization will be required.

***Economic Significance of Innovation*:** The National Science Foundation has stated in the 2001 publication Societal Implications of Nanoscience and Nanotechnology that "Nanoscale science and engineering will lead to better understanding of nature; advances in fundamental research and education; and significant changes in industrial manufacturing, the economy, healthcare, and environmental management and sustainability." NSF further predicts that the worldwide market of nanotechnology-related products will be the size of over $1 trillion annually in 10 to 15 years. In addition in its 2004 report, Sizing Nanotechnology's Value Chain LUX Research was even more optimistic indicating that in 2004 the value of nanotechnology related products was $158B and it is expected that this number would increase in the next 10 years 18x over to about $2.9T in revenue with 89% of that being generated from new technologies

***Technical Barrier to the Innovation*:** Laboratory-based SEM instruments currently operate at levels below those needed for complex nanocharacterization with respect to spatial resolution, chemical sensitivity, speed of data acquisition, and signal to noise. For nanomanufacturing needs, SEM instrumentation is also insufficiently automated, robust, amenable to production environments, and affordable.

***Stage of Innovation Where Barrier Appears*:** R&D and Production

***Measurement-Problem Part of Technical Barrier*:** The priority challenges of nanoscale SEM characterization fall along four interrelated components of metrology: (1) the ability to characterize nanoscale structures in three dimensions, (2) the ability to acquire nanoscale data in a timeframe that supports timely interpretation of the results, (3) the ability to measure complex structures with nanoscale compositional heterogeneity, and (4) the ability to establish the dispersion of nanoscale materials.

***Potential Solutions to Measurement Problem*:** Research is required, in collaboration with instrument manufacturers, to extend the capabilities to the upper theoretical limits of what can be realized in terms of spatial resolution, chemical sensitivity, speed of data acquisition, and signal to noise. Measurements at these length scales have not been done and much needs to be learned about specimen/electron beam interactions and effects upon the ultimate resolution possible and beam irradiation effects on nanometer sized samples. For example, the development and installation of aberration-corrected lenses for the SEM is anticipated have a positive affect on resolution and complex structural characterization ability.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Current flow in nanoscale electronic devices

***Submitter*:** Richard E. Harris (for EEEL)

***Technological Innovation at Stake*:** Full understanding or measurement techniques for electrical current flow in nanoscale electronic devices is critically needed. Progress to date has been made in the absence of this information, but the lack of these data/techniques impedes medium to long-term innovation in these widely used electronic systems. The technical basis of the entire electronics and computing industries is now dominated by electronic integrated circuits having typical critical dimensions well less than 100 nm. All observers expect this trend toward smaller sizes to continue for the foreseeable future, even if it eventually requires moving beyond the present technology based on silicon devices.

***Economic Significance of Innovation*:** The combination of the worldwide electronic and computer industries is hundreds of billions of dollars per year. Should these industries be limited by fundamental understanding or lack of measurement capability, a significant fraction of both industries could be jeopardized.

***Technical Barrier to the Innovation*:** What is needed by design engineers of these complex integrated circuits is the ability to measure and understand their behavior. Ultimately that must be reduced to computer code to permit automatic design at size scales approaching a few atoms. A trial-and-error approach is useless at these levels of complexity.

***Stage of Innovation Where Barrier Appears*:** R&D, Production

***Measurement-Problem Part of Technical Barrier*:** For accurate diagnosis and understanding of individual nanoscale electronic devices it is essential that current flow be understood. In both silicon and all other anticipated electronic devices it is not possible to measure electrical performance of devices at their required speeds of operation when combined with spatial resolution. Integrated circuits that must operate at tens of GHz (billions of operations per second) can only be measured at tens of thousands of operations per second, a factor of about a million times too small.

***Potential Solutions to Measurement Problem*:** There may be a wide variety of measurement solutions available from superconducting electronic techniques involving SQUIDs (superconducting quantum interference devices) to high frequency optical approaches. The solutions may well involve significant interdisciplinary approaches.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Standards for Autoantibody Assays in Autoimmune Disease (AD) and Cancer.

Submitter: John Elliott and Michael Amos, NIST for Antibody-Based Metrology USMS Workshop

Technological Innovation at Stake: A new generation of up to fifty new autoantigens is being developed for use in cancer autoantibody testing. Autoantibodies are important serum analytes for prediction, diagnosis, and treatment of Autoimmune Disease (AD) – including diabetes, rheumatoid arthritis, and lupus – and cancer, for which autoantibodies are a very early-appearing diagnostic biomarker.

Economic Significance of Innovation: According to the NIH, AD affects at least 23 million people in the U.S and costs $400 billion per year. At $92 billion, the annual healthcare costs for diabetes, which is an AD, is higher than that or cancer at $64 billion. Inaccurate autoantibody tests in AD lead to misdiagnosis and associated higher morbidity and mortality. With the advent of autoantibody tests for early diagnosis of cancer, accuracy is even more important. More accurate testing for autoantibodies would enable earlier diagnosis and reduced costs for AD and cancer.

Technical Barrier to the Innovation: There are variabilities in the results of antigen-based diagnostic assays of autoantibodies due to uncontrolled variations in the autoantigens. Autoantibodies (serum analytes) are captured from serum by immobilized autoantigens and impurities and structural integrity issues of the autoantigens impede the reliability of the diagnostic assays based upon them.

Stage of Innovation Where Barrier Appears: R & D

Measurement-Problem Part of Technical Barrier: Low accuracy in measurement of autoantibodies is largely caused by impurities and structural problems with the autoantigens used in the assays, lack of inter-assay correlation and the lack of characterized patient samples with defined autoantibody profiles.

Potential Solutions to Problem: Well-characterized panels of serum analytes as standards and standardized autoantigens are needed. These would include standard reference materials for autoantigens (specific proteins, nucleoprotein complexes, nucleic acids, phospholipids). Each would need be produced, purified and characterized and evaluated for structural integrity and epitope availability by physical and chemical analytical methods, including 1) protein identification, production isolation and sequencing, 2) structural and physical analysis for proteins, DNA and lipids affinity reagents, 3) assay development with clinical correlation, and 4) procedures to confirm epitope integrity. Standardized procedures and reference standards would allow conversion between the readout scales in the different assay platforms, fluorescence intensity standards and procedures for using the standards for immuno-fluorescence autoantibody assays, liquid optical density SRMs for calibrating and standardizing enzyme-linked autoantibody assays and standard reference serum analyte standards for each disease group. Standard statistical methods for establishing clinical relevance of an autoantibody measurement.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Diagnostic Tissue Imaging

***Submitter*:** Grady White

Technology Innovation at Stake: Complexities of tissue composition, chemical interactions, and physical behavior mean that response to stimuli, e.g., from a drug or tumor, cannot be adequately traced or understood by monitoring images based upon a single analyte. Multiplexing, the ability to track multiple analytes simultaneously, potentially addresses this limitation, providing improved basic understanding and a more complete picture of tissue response to both disease and medical treatment.

***Economic Significance of Innovation*:** There are many small businesses poised to take advantage of the capabilities of multiplexing by developing analytes to address specific diseases. Potential chemical markets are estimated to be in the $100M range. More significant are the potential health benefits to society that would result from more accurate diagnoses and enhanced treatment capabilities derived from more complete understanding of tissue behavior.

***Technical Barrier to the Innovation*:** Accurate image interpretation is limited by three interrelated barriers: lack of fundamental understanding of optical/tissue interactions, inappropriate image processing, and the tendency of people to accept computer generated images as representations of reality. The first of these barriers reflects the current state of scientific understanding and will be gradually removed with improved understanding of the biological systems and closer interactions between biologists and physicists/optical engineers. The second barrier will exist until standardized image processing procedures are developed, defined, and accepted. The third barrier requires education of the user regarding both light/tissue interactions and implications of image processing.

***Stage of Innovation Where Barrier Appears*:** R&D; End Use

Measurement Problem Part of Technical Barrier: The measurement problem is that human interpretation of tissue images can lead to misdiagnoses. This results from a combination of poor understanding of light/tissue interactions, e.g., artifact generation, multiscattering, limited penetration, and concomitant image processing errors based upon faulty assumptions.

***Potential Solutions to Measurement Problem*:** Both improved models incorporating realistic interactions of light with tissue and analytes (e.g., contrast, absorption, resolution, thermal effects, multiple scattering) and software providing flexibility and guidance to the user to reflect changing assumptions and measurement conditions need to be developed. A standard image library needs to be developed for testing these algorithms.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Dual-Energy X-ray Absorptiometry (DXA) Systems – Phantoms

***Submitter*:** Andrew Dienstfrey

***Technological Innovation at Stake*:** The diagnosis and monitoring of many bone diseases relies on DXA. Next-generation DXA systems used to measure bone-mineral density (BMD), will be more accurate, have lower life-cycle operating costs for clinical users, and have the capability to compare results taken on different systems, perhaps based on new phantom technologies and protocols that enable cross-calibrations.

***Economic Significance of Innovation*:** Each year over 1.5 million Americans suffer fractures due to osteoporosis, an event that often leads to a downward spiral in physical and mental health. Treatment costs exceed $14 B per year. In fact, 20 percent of senior citizens who suffer a hip fracture die within 1 year. Due primarily to the aging of the population and the previous lack of focus on bone health, the number of hip fractures in the United States is expected to double or even triple by the year 2020. More accurate DXA systems will significantly reduce economic and social costs. New treatments will emerge as drug benefits currently masked by measurement uncertainties become apparent. Also, longitudinal studies may be plagued by measurement drift that could compromise large and expensive clinical trials. Spinal compressive fractures lower significantly the quality of life and entail economic costs comparable to the economic costs of hip fractures.

***Technical Barrier to the Innovation*:** The lack of technical performance standards, e.g., a standard DXA phantom and standard test and evaluation protocols, prevents resolution of inconsistent bone mineral density (BMD) measurements from different machines and from upgrades of the same machine. Also, the lack of adequate knowledge to effectively control drift over time in measurement results contributes to the variability cited in the 2004 Surgeon General's Report on Bone Health. These two deficiencies make it difficult to design and manufacture the next generation of more accurate DXA systems.

***Stage of Innovation Where Barrier Appears*:** Marketplace

***Measurement-Problem Part of Technical Barrier*:** The following measurements and standards will address the above technology barriers. Existing X-ray phantoms (1) are used without a common reference standard and protocol, (2) may possess poorly characterized X-ray extinction properties, and (3) employ non-standard geometric morphologies. Standardization would improve both scanning accuracy and image analysis. DXA scanners measure X-ray extinction and image bone structures responsible for this extinction. These measurements and image analysis are combined to form an areal bone mineral density value, defined as total bone mineral content divided by the exposed area. Both X-ray extinction and image analysis are fundamental in determining the accuracy of BMD values from DXA scanners.

***Potential Solutions to Measurement Problem*:** Develop accurate phantom technology (hardware and software) that manufacturers can use for performance validation of DXA systems. Develop and introduce traceability and quality assurance protocols to define best practices for DXA scanner calibrations based on quantitative performance measures provided by well characterized phantom technologies.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Dual Energy X-Ray Absorptiometry (DXA) Systems – Statistical Analysis

***Submitter*:** Anne Looker, Centers for Disease Prevention and Control, and Tammy Oreskovic

***Technological Innovation at Stake*:** Integrated software and improved approaches for diagnosis must be included in next-generation DXA systems to increase the accuracy of patient diagnoses and to determine the efficacy of treatment. Next-generation DXA systems used to measure bone-mineral density (BMD), should have lower life-cycle operating costs for clinical users and have the capability to compare results taken on different systems, which are based on new integrated software, reference data, and standard protocols that enable cross-calibrations.

***Economic Significance of Innovation*:** More than 1.5 million bone-disease related fractures occur per year. There are 10 million Americans age 50 and older with osteoporosis, a bone disease, and another 34 million at risk for osteoporosis of the hip. Today, the treatment of fractures due to osteoporosis alone costs over $14 B per year and is expected to increase significantly as the average age of the U.S. population increases. Maintaining and supporting the infrastructure to deliver health care to people with osteoporosis adds substantially to these costs. Improved approaches for diagnosis and integrated software are crucial for reducing morbidity, mortality, and health- and social-care costs associated with bone diseases.

***Technical Barrier to the Innovation*:** Diagnosis of osteoporosis currently is based on the T-score, which is calculated by comparing the patient's bone mineral density (BMD) value with the mean BMD and standard deviation values in a young reference population. The T-score approach was originally developed by the World Health Organization (WHO) for use in epidemiological studies of the hip or spine BMD data. One problem arises from the need to compare patient data with a young reference population, given that absolute BMD values generated by DXA systems from different manufactures differ. Unless a study has been performed to generate an algorithm to provide equivalent BMD values from different DXA systems, each manufacturer will require its own reference dataset, which in turn can lead to discrepant diagnoses caused by differences in the reference databases being used.

***Stage of Innovation Where Barrier Appears*:** Marketplace

***Measurement-Problem Part of Technical Barrier*:** BMD values from DXA scanners and proper statistics are central to a given patient's diagnosis and treatment. Because different DXA manufacturers use different proprietary algorithms to calculate BMD, absolute values of BMD differ on different systems. When interpreting BMD data, the patient's value is often compared with mean and SD of a reference population, which is usually either a young group (to calculate a T-score), or an age-sex-race matched value (to calculate a Z-score). Depending on the reference populations used, inconsistencies in T- or Z-scores can occur.

***Potential Solutions to Measurement Problem*:** Create standardized BMD values across different DXA manufacturers for various skeletal sites and obtain standardized BMD reference data for race/ethnic groups not currently covered in National Health and Nutrition Examination Survey (NHANES). Select a committee to define standard protocols for industry to follow to incorporate these databases and integrated software into DXA systems. Finally, using these databases in clinical settings would include development and integration of software for both new and existing DXA systems.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Dual-Energy X-ray Absorptiometry (DXA) Systems – Edge Location

***Submitter*:** Thomas Hangartner, Wright State University

***Technological Innovation at Stake*:** The diagnosis and monitoring of many bone diseases relies on DXA. Next-generation DXA systems to measure bone-mineral density (BMD) should be compatible to each other based on new edge detection technologies, verified software, and protocols that enable patient results from different systems to be compared. These advanced DXA systems will be more accurate, have lower life-cycle operating costs for clinical users, and have the capability to compare easily results taken on different systems.

***Economic Significance of Innovation*:** Each year over 1.5 million Americans suffer fractures due to osteoporosis, an event that often leads to a downward spiral in physical and mental health. Treatment costs exceed $14 B per year. In fact, 20 percent of senior citizens who suffer a hip fracture die within 1 year. Due primarily to the aging of the population and the previous lack of focus on bone health, the number of hip fractures in the United States is expected to double or even triple by the year 2020. More accurate DXA systems will significantly reduce economic and social costs. New treatments will emerge as drug benefits currently masked by measurement uncertainties become apparent. Also, longitudinal studies may be plagued by measurement drift that could compromise large and expensive clinical trials. Spinal compressive fractures lower significantly the quality of life and entail economic costs comparable to the economic costs of hip fractures.

***Technical Barrier to the Innovation*:** The lack of adequate knowledge to consistently locate edges in x-ray images of the hip and spine across platforms makes it difficult to design and manufacture the next generation of more accurate DXA systems.

***Stage of Innovation Where Barrier Appears*:** R&D.

***Measurement-Problem Part of Technical Barrier*:** Consistently locating edges in DXA images requires standardized protocols and algorithms. However, existing edge detection techniques and software (1) do not employ sufficiently similar edge detection techniques to find equal regions of interest, and (2) do not make the same assumptions on what anatomical region to evaluate. The accuracy of BMD values from DXA images depends in part on how well edges are detected and located. DXA scanners measure x-ray extinction and image bone structures responsible for this extinction. These measurements are combined with edge location data to form an areal bone mineral density value, defined as total bone mineral content divided by the exposed area. Both x-ray extinction and image analysis are fundamental in determining the accuracy of BMD values from DXA scanners.

***Potential Solutions to Measurement Problem*:** Measure the impact of scanner drift, variation in x-ray-source intensity and other hardware parameters on the consistency of various edge-detection algorithms; choose best algorithm. Come to an agreement on the anatomical regions to evaluate. Perform the necessary clinical studies to adjust existing normal databases to account for new edge detection and anatomical regions.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue**:** Dual Energy X-Ray Absorptiometry (DXA) Systems – Bone Structure/Geometry

Submitter**:** Thomas Beck, Johns Hopkins University School of Medicine

Technological Innovation at Stake**:** Integrated software to extract bone structure and geometry from DXA measurements would increase the functionality of next generation DXA systems. The development of more quantitative phantoms, which are valid for different models of DXA systems, must be included in next-generation DXA systems. These two innovations will increase the accuracy of patient diagnoses and to determine the efficacies of their treatments.

Economic Significance of Innovation**:** More than 1.5 million bone-disease related fractures occur per year. There are 10 million Americans age 50 and older with osteoporosis, a bone disease, and another 34 million at risk for osteoporosis of the hip. Today, the treatment of fractures due to osteoporosis alone costs over $14 B per year and is expected to increase significantly as the average age of the U.S. population increases. Maintaining and supporting the infrastructure to deliver health care to people with osteoporosis adds substantially to these costs. Improved approaches for diagnosis and integrated software are crucial for reducing morbidity, mortality, and health- and social-care costs associated with bone diseases.

Technical Barrier to the Innovation**:** Lack of integrated software for determining bone structure and its geometry slows the deployment of the next generation of DXA systems. Diagnosis of osteoporosis currently is based on a measurement of bone mineral density (g/cm^2). Bone mineral density is extracted by software from a two dimensional image that over time does not take in account any changes in bone dimensions, such as expansion of the outer surface of the bone with age.

Stage of Innovation Where Barrier Appears**:** Marketplace

Measurement-Problem Part of Technical Barrier**:** The measurement part of the barrier is obtaining by non-invasive techniques the geometric characteristics of bone such as bone area, shape, cortical thickness, and trabecular fraction; and 2) incorporating these characteristics with engineering principles and with DXA bone mineral density (BMD) values in integrated software for improved assessments of bone health. Bone mineral density is a parameter that does not technically equate to bone strength but is used as a surrogate parameter for assessing bone strength. Bone strength from engineering principles is based on outer bone area, inner bone area, thickness of the cortical shell, and other parameters such as elastic coefficients.

Potential Solutions to Measurement Problem**:** Create standardized software that includes geometric characteristics and that could be incorporated in any DXA manufacturers' devices. Select a committee to define standard protocols for industry to follow to incorporate these databases and integrated software into DXA systems.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Dual-Energy X-ray Absorptiometry (DXA) Systems – Bone Mechanical Properties

***Submitters*:** Thomas J. Beck, Johns Hopkins University School of Medicine, and Tammy Oreskovic

***Technological Innovation at Stake*:** The next generation of DXA and ultrasonic systems will lower the costs to assess bone health. Most diseases alter the amount and distribution of bone tissue. Emerging technologies that combine DXA with ultrasound may be able measure geometric features. A number of skeletal diseases alter the mechanical strength of bones so that they fracture easily. Strength loss can be due to differences in the amount and distribution of bone tissue so that load stresses that increase the tissue composition may be altered so that it fails at lower stress. Conventional DXA systems do not provide data on mechanical properties.

***Economic Significance of Innovation*:** More than 1.5 million bone-disease related fractures occur per year. There are 10 million Americans age 50 and older with osteoporosis, a bone disease, and another 34 million at risk for osteoporosis of the hip. Today, the treatment of fractures due to osteoporosis alone costs over $14 B per year and is expected to increase significantly as the average age of the U.S. population increases. Genetic diseases that influence bone tissue properties are not uncommon in children. Treatments for abnormal or altered tissue properties may be very different from that of conventional osteoporosis but current diagnostic methods do not permit them to be distinguished.

***Technical Barrier to the Innovation*:** One barrier is the lack of quantitative ultrasonic properties of bone (hard tissue) and surrounding tissue soft (marrow, tendons, muscle, and fatty tissue). Some osteoporosis treatments alter bone tissue properties and such alterations can only be determined by sophisticated analyses of tissue specimens obtained from painful biopsies. Bone tissue consists of a structured organic matrix containing inorganic mineral, mainly calcium hydroxyapatite. (The marrow and soft tissue components within bones provide insignificant support). The dominant x-ray imaging methods used to evaluate patients only measure the inorganic mineral and not the organic matrix. Theoretically ultrasonic techniques produce signals that are influenced by material composition as well as by bulk density but no commercial system can reliably determine whether the bone tissue in an individual patient is abnormal.

***Stage of Innovation Where Barrier Appears*:** Marketplace

***Measurement-Problem Part of Technical Barrier*:** The challenges are reliable non-invasively measuring mechanical properties of bone tissue and combining the mechanical properties with BMD values from DXA to assess bone health more quantitatively.

***Potential Solutions to Measurement Problem*:** A reliable measurement at an accessible location could be used to determine whether tissue is generally normal and could improve purely geometric evaluations which otherwise assume that the material is normal. A reliable and accurate assessment of elastic (Young's) modulus independent of density effects would suffice.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Next Generation Dual Energy X-Ray Absorptiometry (DXA) Systems

***Submitters*:** Thomas J. Beck, Johns Hopkins University School of Medicine, and Tammy Oreskovic

***Technological Innovation at Stake*:** More quantitative standardized bone mass image and software assessment tools will improve the accuracy of DXA measurements. Common to all methods is that they generate a two-dimensional, single projection digital image in which only bone mineral mass is present and the organic material within and surrounding the bone is subtracted out. Inconsistencies across manufacturers in the location and extent of the imaged area, in the calibration of the pixel values and the location and size of the analyzed regions prevent meaningful comparison of BMD on the same patient when scanned with different systems. Reference standards used for diagnosis also cannot be compared across dissimilar machines.

***Economic Significance of Innovation*:** More than 1.5 million bone-disease related fractures occur per year. There are 10 million Americans age 50 and older with osteoporosis, a bone disease, and another 34 million at risk for osteoporosis of the hip. Today, the treatment of fractures due to osteoporosis alone costs over $14 B per year and is expected to increase significantly as the average age of the U.S. population increases. Maintaining and supporting the infrastructure to deliver health care to people with osteoporosis adds substantially to these costs. The need to duplicate measurements due to inability to compare across different measurement platforms is a significant component of costs.

***Technical Barrier to the Innovation*:** Quantitative and acceptable standardized image formats and software assessment tools are lacking. The several different designs from different manufacturers of dual energy x-ray absorptiometry scanners for measuring bone mineral density (BMD) lead to differences in technology and implementation that in turn give different in results on the same patient. A consistent protocol would permit measurement comparisons across manufacturers and between reference data sets of similar patients.

***Stage of Innovation Where Barrier Appears*:** Marketplace

***Measurement-Problem Part of Technical Barrier*:** One measurement problem is consistently determining the region for linear response of DXA systems. In a bone mass image the pixel value expresses the total bone mass in g/cm^2 integrated along a specific linear projection path through the patient. Differences in calibration and other effects mean that the slope between pixel value and mineral mass in g/cm^2 varies between different systems. The range over which the pixel value is linear will also varies between manufacturers. Differences in software thresholds and in the degree of image blur alter the magnitude of edge detection effects when pixel values are averaged over a region to obtain BMD.

***Potential Solutions to Measurement Problem*:** Create a standardized image format and calibration so that independent of the technology all devices imaging the same patient would produce a digital image with an identical relationship between pixel value and mineral mass. Create standard ‘NIST’ region locations and definitions that generate identical BMD on the same individual (in addition to the proprietary regions).

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** Dual-Energy X-ray Absorptiometry (DXA) Systems – Bone Mass

***Submitters*:** Thomas J. Beck, Johns Hopkins University School of Medicine, and Tammy Oreskovic

***Technological Innovation at Stake*:** The diagnosis and monitoring of many bone diseases relies on DXA. Next-generation DXA systems used to measure bone-mineral density (BMD), will be more accurate, have lower life-cycle operating costs for clinical users, and have the capability to compare results taken on different systems.

Economic Significance of Innovation: Each year over 1.5 million Americans suffer fractures due to osteoporosis, an event that often leads to a downward spiral in physical and mental health. Treatment costs exceed $14 B per year. In fact, 20 percent of senior citizens who suffer a hip fracture die within 1 year. Due primarily to the aging of the population and the previous lack of focus on bone health, the number of hip fractures in the United States is expected to double or even triple by the year 2020. More accurate DXA systems will significantly reduce economic and social costs. Also, spinal compressive fractures lower significantly the quality of life and entail economic costs comparable to the economic costs of hip fractures. The need to duplicate measurements due to inability to compare across different measurement platforms is a significant component of costs.

***Technical Barrier to the Innovation*:** Lack of consistent protocols and artifact does not permit measurement comparisons across manufacturers and between reference data sets. Several different designs from different manufacturers of dual energy x-ray absorptiometry scanners are used in the measurement of bone mineral density (BMD), but these differences in technology and implementation lead to differences in results on the same patient. Inconsistencies across manufacturers in the location and extent of the imaged area, in the calibration of the pixel values, and the location and size of the analyzed regions prevent meaningful comparison of BMD values on the same patient when scanned with different systems. Reference standards used for diagnosis also cannot be compared across dissimilar machines.

***Stage of Innovation Where Barrier Appears*:** Marketplace

***Measurement-Problem Part of Technical Barrier*:** Measuring BMD over a physiologic range of bone thicknesses and bone densities is a great challenge. In a bone mass image the pixel value expresses the total bone mass in g/cm^2 integrated along a specific linear projection path through the patient. Differences in calibration and other effects mean that the slope between pixel value and mineral mass in g/cm^2 varies between different systems. The range over which the pixel value is linear will also varies between manufacturers. Differences in software thresholds and in the degree of image blur alter the magnitude of edge detection effects when pixel values are averaged over a region to obtain BMD.

***Potential Solutions to Measurement Problem*:** To verify that the system is operating within its design specifications and that it is calibrated properly, develop two standard test objects: one test object evaluates the slope and linearity of the pixel mass relationship and the other test object, an anthropometric phantom evaluates the ability to two different DXA systems to provide the same BMD value. Also, these two test objects would be used to determine whether correct BMD values are obtained over a physiologic range of bone thicknesses.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Universal Broadband Access via Optical Fiber

***Submitter*:** Tim Drapela

Technological Innovation at Stake When realized, the new technology – called passive-optical-network (PON) FTTx – will allow access to true broadband telecommunications by virtually every business, organization, and private home in the United States.

Economic Significance of Innovation Annual U.S. telecommunications spending will exceed $1 trillion by 2007. Worldwide, passive-optical-network (PON-FTTx revenues grew 240 % from 2002 to 2003, and U.S. service providers (telcos as well as cable companies) are in the midst of spending roughly $10 billion on FTTx deployment. Full realization of myriad other technologies (telemedicine, telecommuting, distance learning, IP-based voice and video, etc.) is critically dependent on universal "true broadband" access. President George W. Bush has called for affordable broadband access for all Americans by 2007, but the U.S. lags behind major trading partners/competitors in broadband deployment, ranking 13th (and declining) in 2004.

Technical Barrier to the Innovation Development of a nation-covering system of passive FTTx technology, which promises to deliver the Gigabit per second per household projected to be needed for true universal broadband access, is impeded by lack of compatibility among various deployments of PON, lack of protocols for handshakes between user premises and the head-end of the system, and lack of interoperability of equipment from different vendors.

Stage of Innovation Where Barrier Appears Development and Marketing

Measurement-Problem Part of Technical Barrier:There is an inability to validate PON links with splitters and multiple paths where unique identification of particular paths is crucial. For PONs, there are limitations with measurement equipment traditionally used for identifying unique optical paths in branched configurations, such as such as optical time-domain reflectometers [OTDRs] and optical-power-meters.

***Potential Solutions to Measurement Problem*:** There are a number of related aspects of the overall solution to the measurement problem: (1) development of optical frequency-domain reflectometers (OFDRs) suited to characterization of PON links; (2) improved wavelength traceability for various wavelength bands in FTTx; (3) development of documentary standards to address protocol handshakes, transverse-compatibility, interoperability, and the means to monitor and validate them.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Transverse Compatibility in Fiber Optic Transport Networks

***Submitter*:** Tim Drapela

Technological Innovation at Stake The new technology is what is called the black-box system of optical-fiber links and rings that allows complete interoperability among elements throughout an broad-band optical-fiber telecommunication system as the system grows and is modified. Optical fiber links (fiber plus optical amplifiers and associated electronics) and rings (link plus associated wavelength-division multiplexing [WDM] components) are elements critical to metro-based and long-haul optical-fiber telecommunication networks tens to hundreds of kilometers in length. Black links/rings are fully transverse compatible, scaleable, and able to evolve, independent of configuration changes (addition, deletion, substitution, or enhancement of electronic or optical components).

***Economic Significance of Innovation*:** Annual U.S. telecommunications spending will exceed $1 trillion by 2007; worldwide, such spending will surpass $2.5 trillion in 2006. Myriad other technologies (telemedicine, telecommuting, distance learning, IP-based voice and video, etc.) are critically dependent on broadband communications, but broadband access growth is crippled if sufficient backbone capacity is not present. U.S. leadership in achieving transverse compatibility through black link/ring approaches ensures open and free markets internationally.

Technical Barrier to the Innovation There is incomplete technical knowledge and inadequate methods for characterizing the performance of black-box optical-fiber links and rings in broad-band optical-fiber telecommunication systems. With a black link incorporating amplifiers and dispersion-management electronics and a black ring incorporating WDM components, there is a major problem in inferring performance of black link/ring systems from the stated performances of the individual components. Static characterization of individual components does not well correlate to performance in dynamic links or rings, when, for example, amplified spontaneous emission (ASE) of an amplifier is caused by other components.

***Stage of Innovation Where Barrier Appears* (R&D, Production, Marketing, End Use)** R&D

***Measurement-Problem Part of Technical Barrier*:** There is currently an inability to adequately measure key attributes of black-box optical-fiber links and rings, including optical signal-to-noise ratio (OSNR), residual dispersion, characteristics of components at transceiver entry/exit points, and intra-channel and inter-channel crosstalk in the presence of various devices.

***Potential Solutions to Measurement Problem*:** Development of real-time transparent measurement capabilities for OSNR, crosstalk, and dispersion, regardless of components present; development of documentary standards specifying black link/ring approach and, hence, ensuring transverse compatibility.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Fiber-Optic Sensors for National Physical Infrastructure Monitoring

***Submitter*:** Sarah Gilbert, Kent Rochford

Technological Innovation at Stake The new technology is that of networks of fiber-optic sensors on the nation's buildings, bridges, dams, flood barriers, and pipelines to monitor their structural integrity and avoid failure through the sensing of the strain, temperature, and pressure within the structures. The sensors – themselves fiber optics –, are small, lightweight, and immune to electromagnetic interference and they can be monitored remotely via other optical fibers. Unlike conventional sensors, hundreds of fiber-optic sensors can readily be multiplexed to form an extensive multi-parameter sensor network.

Economic Significance of Innovation The sensor industry is near $50 billion in worldwide sales with the fiber optic sensing forecast to exceed $1 billion in 2008. Distributed sensing via optical fiber has the potential to greatly expand the use of sensors and revolutionize our ability to assess structural integrity. Compromise of structural integrity of the nation's physical infrastructure can come about slowly from aging or catastrophically quickly from earthquake or terrorist attack. In terms of aging, of 576,000 bridges in nation's highway system this system, 187,000 are rated as deficient and vulnerable to structural failure that could be detected by networked fiber-optic sensors. Sensing networks retrofitted on the deficient structures would allow funds to be targeted to repair or replace the bridges that are the most vulnerable. In terms of disasters, sensor networks in flood barriers, such as storm levees, could be used to monitor and predict barrier performance under a variety of conditions and identify needed repairs and upgrading; they could provide early warning of impending collapse, prompting timely evacuation that would save lives. Networked fiber-optic sensors could be used effectively for surveillance in homeland security applications.

Technical Barrier to the Innovation Barriers to widespread implementation of this technology include: lack of reliability data, presence of interoperability problems, poor integration of components and systems, and lack of effective capability to determine address the reliability, integration, and interoperability of these systems.

Stage of Innovation Where Barrier Appears R&D on large-scale multiplexed sensor systems

Measurement-Problem Part of Technical Barrier: The is an absence of technical knowledge on and standard methods for assessing the stability and reliability of the sensors, the reliability of the sensor/structure interface, and the accuracy and reproducibility of sensor interrogation.

Potential Solutions to Measurement Problem Needed are industry standard definitions, measurement techniques and test methods for ascertaining the reliability, integration, and interoperability of networks of fiber-optic sensors that monitor their structural integrity of physical infrastructure such as buildings, bridges, dams, flood barriers, and pipelines. Round robin comparisons with industry and government participants would be effective means of gauging the measurement problems and progress.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Broadband Communications - High-Speed Fiber Optic Communications

Submitter**:** Tim Drapela

Technological Innovation at Stake**:** High speed drives innovation in a variety of optical-fiber applications: multimode fiber (MMF) transmission in metro-access (enterprise) networks; optical backplane communications (ultra-short "board-level" distances); and long-haul fiber network links and systems.

Economic Significance of Innovation**:** Annual U.S. telecommunications spending will exceed $1 trillion by 2007. Myriad other technologies (telemedicine, telecommuting, distance learning, IP-based voice and video, etc.) are critically dependent on broadband communications, and the computing, imaging, and electronics industries benefit from broadband availability. In 2002 Dataquest Inc. modeled the impact of universal "true broadband" implementation, estimating annual U.S. GDP increases of $500 billion for each of the subsequent ten years. Continuing advancements in high-speed fiber communications will avoid a bandwidth bottleneck that could limit the realization of all these related technical and economic advances.

Technical Barrier to the Innovation**:** High-speed optical networks require electronic dispersion compensation (EDC), and consistent (low-noise) stress waveforms for testing/validating EDC are currently lacking. Verification of MMF launch conditions continues to be a challenge in MMF enterprise networks. High-speed fiber links and systems are evolving to data rates at or beyond 100 Gb/s, which exceeds specified performance of current measurement technology and instrumentation. High optical powers raise degradation, heating, and reliability concerns. Advances in optical backplane communications are tied directly to advances in manufacturing/characterization of silicon lasers, array optics, and multi-fiber interconnects.

Stage of Innovation Where Barrier Appears**:** R&D, Production, End Use

Measurement-Problem Part of Technical Barrier**:** Improved procedures for verification and testing of EDC and quantification of MMF launch conditions are needed. Measurement capabilities need to be developed or extended for 100 Gb/s networks, for optical waveform, jitter, bit-error rate (BER), ripple, and higher order effects like polarization mode dispersion (PMD), and the ability to partition different effects or impairments is highly desirable.

Potential Solutions to Measurement Problem**:** Development of next-generation test equipment capable of performance at or beyond 100 Gb/s; development of standard reference receivers, standard stress waveforms, and physical (artifact) standards for MMF launch conditions; development of repeatable inverse EDC signal waveforms; development of specifications and test procedures for optical backplanes.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Instrumentation for Broadband Wireless Modulated-Signal Measurements

***Submitter*:** Kate Remley

***Technological Innovation at Stake*:** The new technology is that of high-capacity broadband wireless computer and telecommunication networks that operate effectively under real-world conditions that give rise to nonlinear amplification and distortion that compromise system performance.

***Economic Significance of Innovation*:** Wireless plays an increasing role in this area: U.S. revenue from broadband wireless services such as Wi-Fi and WIMAX is expected to reach $42.6 billion by 2008. Globally, wireless revenue as a whole will approach almost 49 percent of all telecommunications services revenue (some $1.2T) by the end of 2006, largely spurred by broadband. In the U.S. alone, spending on wireless communications will be $124 billion in 2006.[1] President Bush has called for broadband access for all Americans by 2007.

***Technical Barrier to the Innovation*:** Broadband access to wireless computer and telecommunication networks depend upon the use of complicated modulation formats and broad modulation bandwidths for spectral efficiency. Distortion and interference, which are key indicators of system performance, are difficult to determine within broadband wireless systems with such formats and bandwidths. Technically sound, industry-appropriate procedures and metrics for the determination of broadband system performance do not exist.

Stage of Innovation Where Barrier Appears R&D

***Measurement-Problem Part of Technical Barrier*:** It is difficult to independently verify the performance of electrical measurement instrumentation for broadband wireless systems, since these instruments are currently at the cutting edge of measurement technology. In some cases, this leads to a “chicken and egg” dilemma for the wireless test industry. For example, a broadband source may be used to characterize a receiver, which is then used to characterize the source. In other cases, proposed architectures that would enable broadband measurements require new calibrations and/or independent verification, neither of which is available. The inability to carry out accurate and verifiable testing for broadband wireless systems is due to limitations in both existing measurement hardware and measurement science.

***Potential Solutions to Measurement Problem*:** Innovative demodulation and signal-processing techniques are needed to extend the bandwidth of narrow-band/high-dynamic range electrical instruments, in particular, time-domain techniques for characterizing networks that affected by nonlinear amplification and distortion. Traceable broadband sources and receivers would allow manufacturers to use transfer standards to calibrate their systems. Standardized procedures and metrics are needed to verify broadband system performance.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Quality Control in Cytometry for Improved Clinical Diagnostics

Submitter: Adolfas Gaigalas, Lili Wang, and Michael Amos

Technological Innovation at Stake: Quality control and assurance of the performance of flow cytometers are critical to the reliability of clinical assays of antibody expression associated with the occurrence of various diseases. Flow cytometers are complex instruments based upon optical fluorescence methods for detecting individual cells and molecules passing through the instrument. These are marked with molecular probes indicative of particular cell functions or molecular characteristics. The probes contain dyes for optical detection. Marking or staining methods are specific to molecular structure or cell surface receptor type. Different color dyes mark specific structural or receptor types to indicate multiple functionalities in the cells of interest.

***Economic Significance of Innovation*:** The flow cytometry supported disease state assay market was estimated to be ~$1 B/yr in 2004, continues to grow at a rate of approximately 12% per year, and is supported by the flow cytometer instrumentation sector having sales of ~$860 M/yr. A significant part of testing cost is that of repeat testing due to ambiguities resulting from measurement procedures and instrumentation. Improved quality assurance of assay results could decrease regulatory compliance costs, improve clinical lab efficiency, and minimize the high cost of repeat testing.

***Technical Barrier to the Innovation*:** Validation of signals from all of the different labeled probes is a major obstacle to improved diagnoses. No widely accepted method for verifying the operation of a multicolor flow cytometer, e.g., instrument linearity, dynamic range and sensitivity, exists. Instrument validation standards are critical to insure the reliability and accuracy of quantitative measurements in multicolor flow cytometry.

***Stage of Innovation Where Barrier Appears*:** Marketplace

***Measurement-Problem Part of Technical Barrier*:** Although microspheres, resin beads in the 2 to 10 micrometer diameter range, are currently used for instrument performance evaluation, significant improvements are needed to enhance measures of instrument linearity and sensitivity. The wide spectral features associated with fluorophores in solution result in cross talk among the various fluorescence wavelength channels. Reliable corrections are needed to characterize this effect; additionally, new methods to characterize noise sources in these instruments are needed. Improved characterization of dynamic range is important because some abnormal cell markers such as ZAP70 fluoresce dimly while other markers, e.g., for Hairy cell leukemia, are very bright.

Potential Solutions to Measurement Problem: Widely accepted, well-characterized standard artifacts, a set of microspheres having seven fluorophore populations each having different amounts of fluorophores, will provide users with a uniform basis to evaluate individual instrument performance. Populations would be characterized for variation in embedded fluorophore number, absorbance and for emission spectrum. Microsphere size and distribution determination are needed. Well-characterized microsphere populations will support instrument linearity, noise, and dynamic range measurement. New protocols are needed to separate instrument noise from inherent fluorescence signal variation of typical microsphere populations.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Advanced Measurements for Auto-Immune Diseases and Cancer Detection

Submitter: Lili Wang, Adolfas Gaigalas, and Michael Amos

Technological Innovation at Stake: Quantitative multicolor cytometer assays are used by clinical laboratories to estimate the relative number of cells and the number of specific receptor sites on the surfaces of lymphocytes taken from the blood, lymph nodes, bone marrow and other fluids. The capability to measure the absolute number of receptor sites has potential to provide new indicators of cell properties, lineage, clonality, differentiation stage, and activation state, which will be a significant advance in diagnostic capabilities in medicine and healthcare.

***Economic Significance of Innovation*:** The market figure for flow cytometry instrumentation is $860 million per year. Their use in the clinical diagnostic industry accounts for approximately $1B/yr and is growing at 12% per year. Improved standards and methodologies would permit accurate determination of the absolute amounts of cell receptors relevant to diagnosis, allow new diagnostic capabilities, shorten the diagnostic time, increase diagnostic accuracy, and significantly decrease the cost of patient cares.

***Technical Barrier to the Innovation*:** The lack of measurement standards and protocols supporting quantitative cytometer measurements significantly impedes their use for quantitative measurements.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Improved standards will enable the quantitative determination of fluorescence intensity, the amount of light, observed from fluorophore-decorated cells transiting the optical detection section of a cytometer. Fluorescence intensity of six or more different fluorophores will be related to the number of corresponding labeled probes on the surface of the cell. The fluorescence intensity will be converted to fluorescence yield defined as the product of the number of fluorophores and the quantum yield. The comparison of the fluorescence yield of six or more different fluorophores requires thorough examination of the underlying scientific basis and the establishment of a detailed and rigorous protocol. The quantitation of a single fluorophore has been developed in terms of MESF (molecules of equivalent soluble fluorophore) units. Relating quantitatively the response of different fluorophores is the major hurdle. The quantitation protocol would be implemented differently for each assay however the manner in which the protocol is implemented would be general.

Potential Solutions to Measurement Problem: Develop methodology for simultaneously comparing the fluorescence yield of six or more different fluorophores to a corresponding set of calibrant microspheres. The calibrant microspheres would consist of several populations of microspheres with different amounts of surface labeled fluorophores. At first it will be necessary to develop calibrant microspheres for each of the six or more different fluorophores used in a particular multicolored assay. By associating the fluorophores with different antibodies it will be possible to implement quantitation in many different assays.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Diagnostic Flow Cytometry

Submitter: Marla Dowell, Paul Williams, Adolfas Gaigalas, Grady White, and Jeeseong Hwang, USMS Workshop on Biophotonic Tools for Cell and Tissue Diagnostics

Technological Innovation at Stake: The multi-color flow cytometer is a new technology for analysis of the surface receptors on single cells in fluid suspension. Flow cytometry is the principal technique by which clinics can perform multi-parametric quantitative assays of cell characteristics in fluid suspension, a means to improvement in diagnosis of disease and a decrease in a cost of health care.

***Economic Significance of Innovation*:** The market figure for flow cytometers is currently $860 million per year, while the total market figure for the industry they are used in is $1 billion and growing at 12% per year.

***Stage of Innovation Where Barrier Appears*:** R&D

Technical Barrier to the Innovation: Development and effective use of multi-color flow cytometry for quantitative analysis of the cell receptors is impeded by the absence of a means to tie the relative results of the cytometry to known values. A standard technique would be by comparison of the fluorescence yield of labeled cells with that of microspheres with fluorophores immobilized on their surfaces. Well-characterized fluorophore-microsphere reference standards do not exist.

Measurement-Problem Part of Technical Barrier: There is no established method to accurately characterize the fluorescence of microspheres with fluorophores immobilized on their surfaces. Such characterization requires determination of two key photophysical properties of fluorophores, their quantum yield and their absorbance. The quantum yield of the fluorophores depends upon fluorsopore emission states, including resonant emissions; the absorbance of the fluorophores depends on a complex process of scattering of the microsphere. There is no satisfactory modeling of this photo-physical behavior of fluorophores on the surface of microspheres, neither process is adequately understood and theoretically modeled.

Potential Solutions to Measurement Problem: A solution to the problem is development of standard reference microspheres with fluorophores immobilized on the their surfaces with well-characterized fluorescence yield based on accurate determinations of fluorophore quantum yield and absorbance. The measurement of absorbance of fluorophores immobilized on microspheres is best performed using spectrophotometers with integrated sphere detectors designed with filters to minimize interference from fluorescence. Emission properties may be measured using techniques borrowed from single molecule spectroscopy. The measurement of the properties of a single microsphere provides a means to check the uniformity of response in a population of microspheres. The emission properties have to be modeled properly, and the results checked with measurements. The fluorophore quantum yield can be modeled based upon states for the radiation field. For fluorophores immobilized on antibodies in solution, possible photon states can be approximated by plane waves; those on microspheres, by spherical waves satisfied boundary conditions on the surface of the microsphere. Emission resonances due to microsphere resonant states have to be investigated.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue**:** Hard Disk Particle Contamination

Submitter: Paul Webb, Western Digital; Rudy Boynton, Western Digital; Charlie Brown, Hitachi Data

Technological Innovation at Stake: Hard disk drive manufacturers are attempting to develop the next-generation computer hard disk drive systems (HDDs) that will attain the information storage capacities in terms of the Terabits-per-square-inch densities projected by the INSIC (Information Storage Industry Consortium) technology roadmap. These higher-capacity systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

Economic Significance of Innovation**:** The global disk storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large, and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with hard disk drive shipments of more than 400 million units per year. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability, translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

Technical Barrier to the Innovation**:** Future-generation hard disk drives, with terabits-per-square-inch information densities, will require design tolerances that are beyond the current state of knowledge. In addition, new, superior instrumentation is required in order to achieve the requisite monitoring and control of the hard disk drive production processes. Contamination of hard disk drives by particles is a major mechanism of unreliability and failure that becomes more prevalent with the decreasing dimensions and tightening tolerances inherent to next-generation disk drives. Currently, industry is unable to sufficiently monitor, characterize and control these particulates.

Stage of Innovation Where Barrier Appears**:** Production

Measurement-Problem Part of Technical Barrier**:** Manufacturers and suppliers control parts and processes with ultrasonic removal methods and by measurement in Liquid Particle Counter (LPC) systems. Correlation and calibration within and across user groups is inadequate. Current systems are calibrated with polystyrene latex (PSL) spheres that do not represent the actual particle types causing issues in hard drives.

Potential Solutions to Measurement Problem: Development of industry-standardized, accurately calibrated solutions of particles that are more representative of particle morphology, size distribution, and index of refraction of contaminant particles is needed. These solutions of particles must also be shelf stable, unaffected by shipment in anticipated conditions, and provide consistent particle load with predictable removal patterns using conventional equipment.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Gram Force in Hard Disk Drive (HDD) Systems

Submitter: Brett Holaway, Hutchinson Technology, Inc.

Technological Innovation at Stake: Next-generation computer-memory HDDs are being sought by computer system manufacturers that will attain the information storage capacities (Terabits-per-square-inch densities) projected by the INSIC (Information Storage Industry Consortium) technology roadmap. These higher-capacity systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

***Economic Significance of Innovation*:** The global disk storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large and significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with hard disc drive shipments of more than 400 million units per year. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers, increased sales and profits for industrial firms, and greater global market share for U.S. companies.

***Technical Barrier to the Innovation*:** The roadmap-projected terabits-per-square-inch information densities of future-generation hard disc drives require device design tolerances that are beyond the state of knowledge and instrumentation needed for the levels of monitoring and control of the production processes needed to achieve them.. There is inadequate capability to characterize Gram Force (the force applied to the air bearing on the slider towards the disk surface by the head gimbal assembly (HGA) of the HDD that balances out the lift forces to create the fly height of the head over the surface of the recording media), one of the critical tolerance parameters to be specified to achieve interchangeable parts among vendors of head suspensions, head gimbal assembly (HGA), and head stack assemblies (HSA) of HDDs.

Stage of Innovation Where Barrier Appears: Production

Measurement-Problem Part of Technical Barrier: There is no industry-standard method for the measurement of Gram Force and there are substantial variations of results within and among the different measurement systems in use. There is no industry-standard reference artifact for the calibration of Gram-Force measurement systems. The typical reference artifacts for Gram Force measurements are production head suspensions and head gimbal assemblies, which being vulnerable to damage with handling, are not reliable calibration standards.

Potential Solutions to Measurement Problem: What is needed is an industry-recognized gold-standard calibration artifact for gram force measurement (Gram) of a head gimbal assembly (HGA). A proposed approach is development of low-stress cantilever beams of specified geometry, material, manufacturing, and certification method and that are robust under handling and shipping. Ceramic and STT are proposed materials.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Hard Disk Head-Disk Friction

Submitter: James D. Kiely, Seagate Technology

Technological Innovation at Stake: Hard disk drive manufacturers are attempting to develop the next-generation computer hard disk drive systems (HDDs) that will attain the information storage capacities in terms of the Terabits-per-square-inch densities projected by the INSIC (Information Storage Industry Consortium) technology roadmap. These higher-capacity systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

***Economic Significance of Innovation*:** The global disk storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large, and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with hard disk drive shipments of more than 400 million units per year. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability, translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

***Technical Barrier to the Innovation*:** Future-generation hard disk drives, with terabits-per-square-inch information densities, will require design tolerances that are beyond the current state of knowledge. In addition, new, superior instrumentation is required in order to achieve the requisite monitoring and control of the hard disk drive production processes. Contact between the read/write heads and the disk are a cause of failure of HDDs, with increased friction being the indicator of contact. There is no known technology to adequately detect and characterize the head-disk interface friction events of next-generation HDDs.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** There are no off-the-shelf solutions to the problem of measuring head-disk friction of next-generation HDDs. Current friction-measurement methods lack the required precision, sensitivity, frequency response, and freedom from drift, to deal adequately with isolated individual and high-frequency intermittent head-disk contact events. Existing strain gauge technologies are not sufficiently sensitive, are prone to drift and have low bandwidth (1 kHz at best).

Potential Solutions to Measurement Problem: What is needed is an industry-standard method for the drift-free, high-bandwidth, high-sensitivity measurement of head-disk contact friction compatible with existing test equipment. To achieve the required 1µN sensitivity, 0.1 µN precision, 1 MHz bandwidth, and less than 0.1% per hour drift, new measurement technology (perhaps MEMS-based) is needed. The sensors need to be easy to use and sufficiently robust for daily use by operators and technicians. A self-calibrating feature is desirable.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Hard Disk Drive Lubricant Film Roughness

Submitter: Jing Gui, Seagate Technology

Technological Innovation at Stake: Hard disk drive manufacturers are attempting to develop the next-generation computer hard disk drive systems (HDDs) that will attain the information storage capacities in terms of the Terabits-per-square-inch densities projected by the INSIC (Information Storage Industry Consortium) technology roadmap. These higher-capacity systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

***Economic Significance of Innovation*:** The global disk storage market is \$60B. The U.S. share is approximately 40%. The data storage industry is large, and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with hard disk drive shipments of more than 400 million units per year. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability translate to hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

***Technical Barrier to the Innovation*:** Future-generation hard disk drives, with terabits-per-square-inch information densities, will require design tolerances that are beyond the current state of knowledge. In addition, new, superior instrumentation is required in order to achieve the requisite monitoring and control of the hard disk drive production processes. In next-generation hard disk systems, the surface roughness of the lubricant film effects head flying stability and overall drive reliability. At present, there is no means to adequately characterize lubricant surface roughness to allow the design of a more reliable head-disk interface and hence more reliable hard disk drives.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** There are no off-the-shelf solutions; there is no known measurement technology that can measure the surface roughness of the lubricant film on a magnetic hard disk because of the variability in thickness and conformance of a lubricant to the surface of a magnetic disk made up of several different layers of material. X-Ray Reflectivity (XRR), can measure roughness of relevant materials on well-defined under-layers, but cannot be used effectively on the complex films structures of hard disks. Further, it lacks the spatial resolution required to determine the film roughness wavelength.

Potential Solutions to Measurement Problem: A metrology tool is needed to measure lubricant surface roughness with: a 1 nm spatial resolution; an accuracy of better than 0.1 nm; a sampling area of at least 1 μm^2; a temperature range of at least 5° C to 75° C and preferably from -5° C to 95° C; a relative humidity from 0% to 95%; and a measurement time under 1 hour. An XRR with a reduced spot size seems feasible.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Thin Film Function and Stability for Hard Disk Drives

Submitter: Peter Baumgart, Hitachi Global Storage Technologies

Technological Innovation at Stake: Hard disk drive manufacturers are attempting to develop the next-generation computer hard disk drive systems (HDDs) that will attain the information storage capacities, in terms of the Terabits-per-square-inch densities, projected by the INSIC (Information Storage Industry Consortium) technology roadmap. These higher-capacity systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

***Economic Significance of Innovation*:** The global disk storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large, and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with hard disk drive shipments of more than 400 million units per year. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

***Technical Barrier to the Innovation*:** Future-generation hard disk drives, with terabits-per-square-inch information densities, will require design tolerances that are beyond the current state of knowledge. In addition, new, superior instrumentation is required in order to achieve the requisite monitoring and control of the hard disk drive production processes. For next-generation recording media, the number of thin-film layers is increased, their structures made more complex, and their thickness reduced to the single nanometer range, where the mechanical function and stability of those film structures are critically dependent upon unknown mechanical properties.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Current techniques used to measure mechanical properties such as hardness, yield strength, and other elastic and plastic properties of thin films, rely on stylus- (or AFM) derived approaches and are inadequate to the needs of characterization of next-generation hard disk heads and media. This inadequacy occurs because these approaches have response depths of at best about one hundred nm.

Potential Solutions to Measurement Problem: A solution is the development of (1) new indentation and surface probing techniques that measure mechanical properties of the top few nanometers of material with ultra-small force deformation and response depth; and (2) calibrated nano-mechanical reference standards for hardness, yield and shear strength for films thinner than 2 nm.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Static Attitude-Hard Disk Drive (HDD) Systems

Submitter: Brett Holaway, Hutchinson Technology, Inc.

Technological Innovation at Stake: Next-generation computer-memory HDDs are being sought by computer system manufacturers that will attain the information storage capacities (Terabits-per-square-inch densities) projected by the INSIC (Information Storage Industry Consortium) technology roadmap. These higher-capacity systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

***Economic Significance of Innovation*:** The global disk storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large and significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with hard disc drive shipments of more than 400 million units per year. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers, increased sales and profits for industrial firms, and greater global market share for U.S. companies.

***Technical Barrier to the Innovation*:** The roadmap-projected terabits-per-square-inch information densities of future-generation hard disc drives require device design tolerances that are beyond the state of knowledge and instrumentation needed for the levels of monitoring and control of the production processes needed to achieve them. There is inadequate capability to characterize static attitude (SA) of a head gimbal assembly (HGA), the angle of the air bearing surface relative to the mounting surface.

Stage of Innovation Where Barrier Appears: Production

Measurement-Problem Part of Technical Barrier: There is no industry-standard method for the measurement of a head-gimbal-assembly static attitude and there are substantial variations of results within and among the different measurement systems in use. There is no industry-standard reference artifact for the calibration of SA measurement systems. The typical reference artifacts for SA Gram Force measurements are production head suspensions and head gimbal assemblies that are not reliable calibration standards, being vulnerable to damage with handling.

Potential Solutions to Measurement Problem: What is needed is an industry-recognized standard calibration artifact for Static Attitude of a head gimbal assembly of specified geometry, material, manufacturing, and certification method and that are robust under handling and shipping.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Torque-Hard Disk Drive (HDD) Systems

Submitter: Brett Holaway, Hutchinson Technology, Inc.

Technological Innovation at Stake: Next-generation computer-memory HDDs are being sought by computer system manufacturers that will attain the information storage capacities (terabits-per-square-inch densities) projected by the INSIC (Information Storage Industry Consortium) technology roadmap. These higher-capacity systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

Economic Significance of Innovation**:** The global disk storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large and significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with hard disc drive shipments of more than 400 million units per year. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers, increased sales and profits for industrial firms, and greater global market share for U.S. companies.

Technical Barrier to the Innovation**:** The roadmap-projected terabits-per-square-inch information densities of future-generation hard disc drives require device design tolerances that are beyond the state of knowledge and instrumentation needed for the levels of monitoring and control of the production processes needed to achieve them. There is inadequate capability to characterize Torque, one of the critical parameters that determine the fly height of the head over the surface of the recording media and that is specified to achieve interchangeable parts among vendors of head suspensions, head gimbal assembly (HGA), and head stack assemblies (HSA) of HDDs.

Stage of Innovation Where Barrier Appears: Production

Measurement-Problem Part of Technical Barrier: There is no method for direct measurement of Torque. Torque currently is estimated via just three of the forces that contribute to head fly height: the average force to push the air bearing down to the disk surface in the Z direction; the moment in the IDEMA Roll Static Attitude (RSA) direction; and the moment in the IDEMA Pitch Static Attitude (PSA) direction. The current design process of HDD heads is iterative with specified Gram Force, PSA, and RSA, assuming a value of stiffness in each of these directions. For next-generation HDD heads, reduction in variations of Gram, PSA and RSA and increased sensitivity of fly height to forces other than these, makes direct measurement of torque necessary.

Potential Solutions to Measurement Problem: What is needed is an industry-standard method for direct measurement of HDD head torque. This will require research into methods to measure torque, development of an effective torque sensor, and certification of a torque calibration artifact. A potential solution is use of MEMS pressure-transducer arrays for torque measurement.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Windage-Hard Disk Drive (HDD) Systems

Submitter: Brett Holaway, Hutchinson Technology, Inc.

Technological Innovation at Stake: Next-generation computer-memory HDDs are being sought by computer system manufacturers that will attain the information storage capacities (terabits per square-inch densities) projected by the INSIC (Information Storage Industry Consortium) technology roadmap. These higher-capacity systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

***Economic Significance of Innovation*:** The global disk storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large and significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with hard disc drive shipments of more than 400 million units per year. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers, increased sales and profits for industrial firms, and greater global market share for U.S. companies.

***Technical Barrier to the Innovation*:** The roadmap-projected terabits-per-square-inch information densities of future-generation hard disc drives require device design tolerances that are beyond the state of knowledge and instrumentation needed for the levels of monitoring and control of the production processes needed to achieve them. Windage, the displacement in the off-track direction due to flow-induced vibration of the head gimbal assembly (HGA), is one of the critical tolerance parameters that must be specified to achieve interchangeable parts among vendors for the actuator sub-assemblies of HDDs. There is inadequate capability to characterize Windage,.

Stage of Innovation Where Barrier Appears: Production

Measurement-Problem Part of Technical Barrier: There is no industry-standard method for the measurement of Windage and there are substantial variations of results within and among the different measurement systems in use. There is no industry-standard reference artifact for the calibration of Gram-Force measurement systems. The typical reference artifacts for Windage measurements are production head suspensions and head gimbal assemblies, which being vulnerable to damage with handling, are not reliable calibration standards.

Potential Solutions to Measurement Problem: What is needed is an industry-recognized calibration artifact for HGA Windage. Calibration artifacts will need modes throughout the range 10 kHz and 150 kHz, with varying amounts of displacement due to the vibration induced by the air flow from a spinning HDD disk. This would allow for calibration of both frequency and displacement across the expected working range of the measurement system. The artifacts need to meet requirements for robustness in handling, mode frequency, displacement, and function loading. Low-stress cantilever beams constructed of ceramics or SST are candidates. IDEMA has a windage definition that may serve as a starting point.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Frequency Response Function in Hard Disk Drive (HDD) Systems

Submitter: Brett Holaway, Hutchinson Technology, Inc.

Technological Innovation at Stake: Next-generation computer-memory HDDs are being sought by computer system manufacturers that will attain the information storage capacities (Terabits-per-square-inch densities) projected by the INSIC (Information Storage Industry Consortium) technology roadmap. These higher-capacity systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

Economic Significance of Innovation: The global disk storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large and significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with hard disc drive shipments of more than 400 million units per year. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability, translate into hundreds of millions of dollars per year, with savings to consumers, increased sales and profits for industrial firms, and greater global market share for U.S. companies.

***Technical Barrier to the Innovation*:** The roadmap-projected terabits-per-square-inch information densities of future-generation hard disc drives require device design tolerances that are beyond the state of knowledge and instrumentation needed for the levels of monitoring and control of the production processes needed to achieve them. The Frequency Response Function (FRF) of the head gimbal assembly is one of the critical tolerance parameters that must be specified to achieve interchangeable parts among vendors of head suspensions, head gimbal assemblies, and head stack assemblies (HSA) of HDDs and there is no effective method to adequately characterize the FRF.

Stage of Innovation Where Barrier Appears: Production

Measurement-Problem Part of Technical Barrier: There is no industry-standard reference artifact for the calibration of these systems. There is no single industry-standard method for the measurement of the frequency response of the HDD head gimbal assembly. Some of components of what could be a FRF measurement system can be calibrated but the system as a whole cannot. There are substantial variations of results within and among the different measurement systems in use.

Potential Solutions to Measurement Problem: What is needed is an industry-recognized gold-standard system for the measurement of Frequency Response Function of the HDD head gimbal assembly. An artifact is needed to calibrate FRF measurements systems in different frequency ranges and amplitude through a range from 10 kHz to 150 kHz with amplitudes from 2 dB to 50 dB when applied to HDD FRF shaker boundary conditions. The artifact needs to be robust to handling and shipping and meet the modal frequency requirements.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Out-gassing Control for Hard Disk Drives

Submitter: Bob Reeves, Maxtor Corp., Deborah Campbell, Maxtor Corp., Steve Crochiere, Maxtor Corp.

Technological Innovation at Stake: Hard disk drive manufacturers are attempting to develop the next-generation computer hard disk drive systems (HDDs) that will attain the information storage capacities in terms of the Terabits-per-square-inch densities projected by the INSIC (Information Storage Industry Consortium) technology roadmap. These higher-capacity systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

***Economic Significance of Innovation*:** The global disk storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large, and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with hard disk drive shipments of more than 400 million units per year. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability, translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

***Technical Barrier to the Innovation*:** Future-generation hard disk drives, with terabits-per-square-inch information densities, will require design tolerances that are beyond the current state of knowledge. In addition, new, superior instrumentation is required in order to achieve the requisite monitoring and control of the hard disk drive production processes. Certain gases emanating from parts and subassemblies inside of hard disk drives react with and interfere with the lubricant on the disk and cause catastrophic failure of the device. The impact of not controlling such out-gassing ranges from an undesirable return rate of defective drives, through recall of products, to the inability to achieve roadmap goals.

***Stage of Innovation Where Barrier Appears*:** Primary: R&D, Secondary: Production

***Measurement-Problem Part of Technical Barrier*:** All hard disk drive and tape drive manufacturers and their suppliers monitor and control volatile organic compounds in hard disk drive parts and subassemblies. This is done by dynamic headspace gas chromatography / mass spectrometry (GC/MS). Uncertainties in measurements, such as false positives, false negatives, and lack of effective correlation between measurement results found by the disk drive manufacturers and their subassembly suppliers, are a major problem.

Potential Solutions to Measurement Problem: An industry-accepted reference standard is needed as a means to achieve confidence in the competence of laboratories to perform this measurement, greater uniformity in measurement results from different laboratories, and greater acceptance of suppliers' measurement results. Such a standard would also provide a basis for qualification of contract laboratories for use by suppliers without laboratories, as well as for certifying chemists to perform the analysis. Two types of reference standards are desirable: (1) a standard mixed-liquid solution to use for spiking samples, adsorbent tubes, or as a check standard; and (2) a standard impregnated-solid with 2-3 compounds that would be stable over time and temperature and that would be very reproducible.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Head Wear in Magnetic Tape Systems

Submitter: Diana J. Hellman, IBM

Technological Innovation at Stake: Computer-memory magnetic tape systems manufacturers are attempting to develop the next-generation magnetic tape systems that will attain the information storage capacities (areal densities) projected by the 2005 INSIC (Information Storage Industry Consortium) International Magnetic Tape Storage Roadmap. These systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

***Economic Significance of Innovation*:** The global data storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large, and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with tape drives having an annual volume of sales of hundreds of thousands per year with millions of magnetic tapes. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

***Technical Barrier to the Innovation*:** The roadmap-projected areal densities of future-generation magnetic tape systems will require design tolerances that are beyond the current state of knowledge. In addition, new, superior instrumentation is required in order to achieve the requisite monitoring and control of the magnetic tape system production processes. Head wear due to abrasion by the tape, which increases head-tape spacing and signal loss, is a major cause of reduced performance and failure of magnetic tape systems. Understanding of the effects of the media as a basis for controlling head wear and predicting head life is limited by the inability to adequately characterize the abrasivity of the tape.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Currently, there is no method that correlates the abrasion property of tapes as measured with the wear of tape heads observed. For a variety of reasons, what is available today are measurements of relative wear involving test materials different than actual head materials.

Potential Solutions to Measurement Problem: What is needed is a new method for characterization of the wear-inducing properties of magnetic tapes on the actual materials of next-generation magnetic heads--that is, a direct measurement of the abrasivity of the tape media.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue**:** Magnetic Tape Protective Coating Thickness

Submitter: Anand Lakshmikumaran, Sun Microsystems; Larry Olson, Imation; Michael Sharrock, Imation

Technological Innovation at Stake: Computer-memory magnetic tape systems manufacturers are attempting to develop the next-generation magnetic tape systems that will attain the information storage capacities (areal densities) projected by the 2005 INSIC (Information Storage Industry Consortium) International Magnetic Tape Storage Roadmap. These systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

Economic Significance of Innovation**:** The global data storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large, and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with tape drives having an annual volume of sales of hundreds of thousands per year with millions of magnetic tapes. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

Technical Barrier to the Innovation**:** The roadmap-projected areal densities of future-generation magnetic tape systems will require design tolerances that are beyond the current state of knowledge. In addition, new, superior instrumentation is required in order to achieve the requisite monitoring and control of the magnetic tape system production processes. Next-generation magnetic tape systems require successive decreases in head/tape spacing. The thickness of the protective layer on the tape needs to be measured and controlled beyond current capabilities.

Stage of Innovation Where Barrier Appears**:** R&D

Measurement-Problem Part of Technical Barrier**:** There is no effective and standardized method for measuring the thickness of the protective coating, including the thickness of the lubrication film, on magnetic tape required to take into account that component of the overall tape-to-head spacing.

Potential Solutions to Measurement Problem: A potential solution to this measurement problem is to adapt, with compensation for the flexibility of the tape, the measurement processes and standards from the hard disk drive (HDD) industry where deposited thin-film, hard-disk media has been used for many years. This could involve use of a static measurement on a small sample of tapes but measurable over a number of locations along the length and width of tape.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Tape Deflection in Magnetic Tape Systems

Submitter: Anand Lakshmikumaran, Sun Microsystems; Larry Olson, Imation; Michael Sharrock, Imation

Technological Innovation at Stake: Computer-memory magnetic tape systems manufacturers are attempting to develop the next-generation magnetic tape systems that will attain the information storage capacities (areal densities) projected by the 2005 INSIC (Information Storage Industry Consortium) International Magnetic Tape Storage Roadmap. These systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

***Economic Significance of Innovation*:** The global data storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large, and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with tape drives having an annual volume of sales of hundreds of thousands per year with millions of magnetic tapes. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

***Technical Barrier to the Innovation*:** The roadmap-projected areal densities of future-generation magnetic tape systems will require design tolerances that are beyond the current state of knowledge. In addition, new, superior instrumentation is required in order to achieve the requisite monitoring and control of the magnetic tape system production processes. Presently there is no effective way to determine and monitor to the degree of tape deflection in next-generation magnetic tape systems.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** There is no effective and standard method for measuring the conformance of the tape into the recessed device area on the tape head, that is, the distance that the flexible tape deflects toward the recessed pole faces as the tape moves over the tape head and over in the tape head.

Potential Solutions to Measurement Problem: One possible technique to measure the conformance of the tape to the head pole faces is to compare the compressed asperity height with and without the tape being in motion, using a glass head having a recessed region. In this case, the metrology requirements would be same as that for the mean compressed tape asperity height. A standardized method and a standard for calibration of the measuring instrument are required.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue**:** Magnetically Inactive Layer on Tape Heads in Magnetic Tape Systems

Submitter: Anand Lakshmikumaran, Sun Microsystems; Larry Olson, Imation; Michael Sharrock, Imation

Technological Innovation at Stake: Computer-memory magnetic tape systems manufacturers are attempting to develop the next-generation magnetic tape systems that will attain the information storage capacities (areal densities) projected by the 2005 INSIC (Information Storage Industry Consortium) International Magnetic Tape Storage Roadmap. These systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

Economic Significance of Innovation**:** The global data storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large, and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with tape drives having an annual volume of sales of hundreds of thousands per year with millions of magnetic tapes. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

Technical Barrier to the Innovation**:** The roadmap-projected areal densities of future-generation magnetic tape systems will require design tolerances that are beyond the current state of knowledge. In addition, new, superior instrumentation is required in order to achieve the requisite monitoring and control of the magnetic tape system production processes. Next-generation magnetic tape systems require successive decreases in head-to-tape spacing. The thickness of the magnetically inactive layer on the head needs to be measured and controlled beyond current capabilities.

Stage of Innovation Where Barrier Appears**:** R&D

Measurement-Problem Part of Technical Barrier**:** While a magnetically inactive layer can be induced on the tape head by machining processes in its fabrication, by tribo-chemical and electro-chemical processes with interaction of shields and poles and recording devices, and by mechanical contact with the tape in operation, there is no effective and standardized method for measuring the thickness of the inactive layer to take into account this component of the overall head-to-tape spacing.

Potential Solutions to Measurement Problem: A potential solution to this measurement problem is development of a standardized method for measurement of the thickness of magnetically inactive (dead) layer on recording device in tape head. Accuracies of better than 0.1 nm are required right now for any technique that is developed and accuracies of better than 0.03 nm will be required by 2015.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Magnetically Inactive Layer on Tape in Magnetic Tape Systems

Submitter: Anand Lakshmikumaran, Sun Microsystems; Larry Olson, Imation; Michael Sharrock, Imation

Technological Innovation at Stake: Computer-memory magnetic tape systems manufacturers are attempting to develop the next-generation magnetic tape systems that will attain the information storage capacities (areal densities) projected by the 2005 INSIC (Information Storage Industry Consortium) International Magnetic Tape Storage Roadmap. These systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

***Economic Significance of Innovation*:** The global data storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large, and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with tape drives having an annual volume of sales of hundreds of thousands per year with millions of magnetic tapes. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

***Technical Barrier to the Innovation*:** The roadmap-projected areal densities of future-generation magnetic tape systems will require design tolerances that are beyond the current state of knowledge. In addition, new, superior instrumentation is required in order to achieve the requisite monitoring and control of the magnetic tape system production processes. Next-generation magnetic tape systems require successive decreases in head-to-tape spacing. The thickness of the magnetically inactive layer on the tape needs to be measured and controlled beyond current capabilities.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** There is no effective and standardized method for measuring the thickness of the magnetically inactive layer on the tape to take into account this component of the overall tape-to-head spacing. This measurement parameter is defined as the distance between the mean of the compressed asperity height and the magnetically active layer on the media.

Potential Solutions to Measurement Problem: A solution to this measurement problem is development of a standardized method for measurement of the thickness of magnetically inactive (dead) layer on recording device in tape head. Accuracy requirements are less than 0.3 nm right now and will be less than 0.08 nm by 2015. This will definitely require a new measurement process and probably a standard.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Dimensional Stability of Media in Magnetic Tape Systems

Submitter: Diana J. Hellman, IBM

Technological Innovation at Stake: Computer-memory magnetic tape systems manufacturers are attempting to develop the next-generation magnetic tape systems that will attain the information storage capacities (areal densities) projected by the 2005 INSIC (Information Storage Industry Consortium) International Magnetic Tape Storage Roadmap. These systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

***Economic Significance of Innovation*:** The global data storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large, and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with tape drives having an annual volume of sales of hundreds of thousands per year with millions of magnetic tapes. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

***Technical Barrier to the Innovation*:** The roadmap-projected areal densities of future-generation magnetic tape systems will require design tolerances that are beyond the current state of knowledge. In addition, new, superior instrumentation is required in order to achieve the requisite monitoring and control of the magnetic tape system production processes. A lack of understanding of the dimensional variability of the magnetic tape due to changing temperature, humidity, and mechanical stress impedes the design and manufacture systems that track accurately when subjected to real operating conditions, resulting in errors in reading and destructive overwriting of data.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** At present, there is no measurement method for the accurate characterization of the changes in dimensional stability of magnetic tapes subjected to the varying environmental and operating conditions to which systems are exposed in actual use.

Potential Solutions to Measurement Problem: What is needed are (1) a standardized method for the accurate measurement of the dimensional stability of magnetic tapes as a function of temperature, humidity, pack stresses, time, and the motion of media flies over the head; and (2) a standardized method for accelerated-aging lifetime testing of the dimensional stability of tapes.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Magnetic Domain Walls in Magnetic Tape Systems

Submitter: John Nibarger, Sun Microsystems

Technological Innovation at Stake: Computer-memory magnetic tape systems manufacturers are attempting to develop the next-generation magnetic tape systems that will attain the information storage capacities (areal densities) projected by the 2005 INSIC (Information Storage Industry Consortium) International Magnetic Tape Storage Roadmap. These systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

***Economic Significance of Innovation*:** The global data storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large, and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with tape drives having an annual volume of sales of hundreds of thousands per year with millions of magnetic tapes. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

***Technical Barrier to the Innovation*:** The roadmap-projected areal densities of future-generation magnetic tape systems will require design tolerances that are beyond the current state of knowledge. In addition, new, superior instrumentation is required in order to achieve the requisite monitoring and control of the magnetic tape system production processes. The performance of thin-film magnetic read heads, which operate by detecting flux transition emanating from the magnetic storage media, degrades when, due to the presence of non-uniform magnetic fields, the preferred single-domain magnetic state of the sensor breaks up into multiple domains. The inability to adequately determine the emergence, location and movement of magnetic domain walls within a tape read head is a technical barrier to development of future-generation magnetic tape systems.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** There is no current measurement technique that can locate and measure the movement of magnetic domain walls within a tape read head, with the dimensions, geometry, and magnetic characteristics of next-generation tape systems.

Potential Solutions to Measurement Problem: A measurement method is needed that can detect, locate and track the movement within tape read heads under static and dynamic magnetic operating conditions. The method must have a high spatial resolution on the order of 5 nm since the thickness of sensors range from 15 to 30 nm and 4 to 10 nm for the two types of magnetic-resonance sensors. Due to the extreme spatial resolution requirements, it would appear that only electron- and cantilever-based technologies are possible. However, the use of near-field optical techniques should not be completely discounted, especially when considering the effects of the shields on the domain structure of the sensor. Electron-based solutions include Scanning Electron Microscope with Polarization Analysis (SEMPA) and cantilever solutions include magnetic force microscope (MFM). A number of potential solutions already exist for this metrology problem. It must be noted that difficulties arise when trying to perform observations of domain structure in an *in situ* environment.

Case Study – Measurement Needs

***Technology at Issue*:** Mechanical Behavior of Tape in Magnetic Tape Systems

Submitter: Douglas W. Johnson, Imation Corporation

Technological Innovation at Stake: Computer-memory magnetic tape systems manufacturers are attempting to develop the next-generation magnetic tape systems that will attain the information storage capacities (areal densities) projected by the 2005 INSIC (Information Storage Industry Consortium) International Magnetic Tape Storage Roadmap. These systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

***Economic Significance of Innovation*:** The global data storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large, and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with tape drives having an annual volume of sales of hundreds of thousands per year with millions of magnetic tapes. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

***Technical Barrier to the Innovation*:** The roadmap-projected areal densities of future-generation magnetic tape systems will require design tolerances that are beyond the current state of knowledge. In addition, new, superior instrumentation is required in order to achieve the requisite monitoring and control of the magnetic tape system production processes.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The development of new and manufacture of current high-density magnetic tape systems is impeded by the ability to continuously and nondestructively characterize the dynamic mechanical behavior of long portions of magnetic tape, specifically the tape cupping, curvature, width, and weave that effect maintenance of the flatness of the tape over a wide surface of the tape path transport.

Potential Solutions to Measurement Problem: Specialized transports can be built; optical techniques can be developed to measure tape edge position that may be used to determine width and weave; cross web tension (stress) or the displacement of magnetic marks on tape (strain) could possibly be used to determine curvature and cupping.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Smooth Tape Motion in Magnetic Tape Systems

Submitter: Gary Collins, Collins Consulting

Technological Innovation at Stake: Computer-memory magnetic tape systems manufacturers are attempting to develop the next-generation magnetic tape systems that will attain the information storage capacities (areal densities) projected by the 2005 INSIC (Information Storage Industry Consortium) International Magnetic Tape Storage Roadmap. These systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

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***Technical Barrier to the Innovation*:** The roadmap-projected areal densities of future-generation magnetic tape systems will require design tolerances that are beyond the current state of knowledge. In addition, new, superior instrumentation is required in order to achieve the requisite monitoring and control of the magnetic tape system production processes. Smooth tape motion with lateral tape motions of less than 1 micron will be needed for track densities of greater than 10,000 tracks per inch. Without the capability to characterize tape motion, tape path developers will not know the degree to which they've improved the tape guiding characteristics of the path, and designers of track-following servo systems will not know the features that need to be built into their servo systems.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Measurement instrumentation with the required resolution, accuracy, portability and cost do not exist. The two primary candidate instruments for measurement of magnetic tape position are both optical-based. The Fotonic probe made by MTI measures lateral *edge* motion, and the Laser Surface Vibrometer made by Polytec measures lateral *surface* motion. Neither instrument meets the measurement needs. The Fotonic probe is limited in resolution at high frequencies, and the Laser Surface Vibrometer is limited in resolution by low S/N ratio because of the low reflectivity of the tape. The Fotonic probe method needs to have its bandwidth increased, and the Vibrometer method needs to amplify the reflected signal in some manner so that a suitable signal may be extracted from a single pass of the tape.

Potential Solutions to Measurement Problem: Development of tape-motion measuring systems and the reference standards needed to characterize their performance and calibrate their output to better than 0.1 micron at frequencies from 0 to 10,000 Hz.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Tape-Edge Variation in Magnetic Tape Systems

Submitter: Ted Schwarz, Peregrine Recording Technology

Technological Innovation at Stake: Computer-memory magnetic tape systems manufacturers are attempting to develop the next-generation magnetic tape systems that will attain the information storage capacities (areal densities) projected by the 2005 INSIC (Information Storage Industry Consortium) International Magnetic Tape Storage Roadmap. These systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

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***Technical Barrier to the Innovation*:** The roadmap-projected areal densities of future-generation magnetic tape systems will require design tolerances that are beyond the current state of knowledge. In addition, new, superior instrumentation is required in order to achieve the requisite monitoring and control of the magnetic tape system production processes. There is an inability to design, characterize, and compare the performance of alternative tape-drive mechanisms of next-generation magnetic tape systems due to the inability to separate variations in tape-path due to the drive from those due to variations in the tape edges.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Attempts to measure variations in tape edges over significant lengths of tape are frustrated by the convolution of variations in apparent position of the tape edge due to the variations in the position of the tape overall due to the tape transport mechanism.

Potential Solutions to Measurement Problem: There is a lack of standardized high-precision methods of the characterization of tape edge variation likely consisting of a combination of (1) a precise, stable transport to serve as a replicable platform, (2) a standardized technique for its use, and (3) reference standards as "golden" standard tape path and media.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Media Properties in Magnetic Tape Systems

Submitter: Dave Pappas

Technological Innovation at Stake: Computer-memory magnetic tape systems manufacturers are attempting to develop the next-generation magnetic tape systems that will attain the information storage capacities (areal densities) projected by the 2005 INSIC (Information Storage Industry Consortium) International Magnetic Tape Storage Roadmap. These systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

***Economic Significance of Innovation*:** The global data storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large, and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with tape drives having an annual volume of sales of hundreds of thousands per year with millions of magnetic tapes. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

***Technical Barrier to the Innovation*:** The roadmap-projected areal densities of future-generation magnetic tape systems will require design tolerances that are beyond the current state of knowledge. In addition, new, superior instrumentation is required in order to achieve the requisite monitoring and control of the magnetic tape system production processes. The media, recording heads, low-field sensors, and isolators of next-generation magnetic tape systems depend on multiple thin-film structures with distinctive geometries and precisely defined magnetic properties. These properties including magnetic coercivity and magnetic moment, which exceed present capabilities to effectively characterize, monitor, and control.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The major challenge is to measure the extremely small magnetic moments of the nanometer-scale thin-films that are part of new-technology magnetic tape systems, such as giant magneto resistance (GMR) sensors. Measurement techniques currently in use are sensitive to the magnetic fields and geometry of the sample that serves as the reference standard. The nearly most suitable reference standards available – ferromagnetic nickel and yttrium-iron-garnet reference materials – are bulk materials with magnetic moments and associated magnetic field strength that are of the order of 200 times too large.

Potential Solutions to Measurement Problem: What is needed is a family of thin-film, low-magnetic-moment reference standards with form factors (thin film geometries) that match those used in industry for the development and manufacture of next-generation magnetic data storage systems.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Pole Tip Recession in Magnetic Tape Systems

Submitter: Anand Lakshmikumaran, Sun Microsystems; Larry Olson, Imation; Michael Sharrock, Imation; Mike Chaw, Hitachi Global Storage Technologies

Technological Innovation at Stake: Computer-memory magnetic tape systems manufacturers are attempting to develop the next-generation magnetic tape systems that will attain the information storage capacities (areal densities) projected by the 2005 INSIC (Information Storage Industry Consortium) International Magnetic Tape Storage Roadmap. These systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

***Economic Significance of Innovation*:** The global data storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with tape drives having an annual volume of sales of hundreds of thousands per year with millions of magnetic tapes. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

***Technical Barrier to the Innovation*:** The roadmap-projected areal densities of future-generation magnetic tape systems will require design tolerances that are beyond the current state of knowledge. In addition, new, superior instrumentation is required in order to achieve the requisite monitoring and control of the magnetic tape system production processes. Next-generation magnetic tape systems require successive decreases in head-to-tape spacing. Of the five parameters of head-to-tape spacing, Pole tip (or device) recession (PTR) is a significant barrier.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Pole tip (or device) recession (PTR)**:** This is the static recession of the recording devices with respect to the arithmetic mean of the tape bearing surface. This includes the amount of recess of the shields/poles from the tape bearing surface as well as the amount of recess of the structures from the surrounding shields/poles. Currently, only the recession of the shields/poles from the tape bearing surface is measured but is reported as PTR; the measurements are made using optical interferometry and atomic force microscope (AFM), without adequate spatial resolution and with inadequate repeatability due to the nature of the curve fits used and variation in optical properties of the surface due to any kind of stain/coating on the tape. Attainable accuracies appear to be order of 3 nm at best. Accuracies of less than 1 nm are required right away and less than 0.4 nm will be required by 2015.

Potential Solutions to Measurement Problem: (1) A PTR step standard reference materials should be developed and made available: (2) Reference standards that reflect the shape of the anticipated recession (for AFM PTR measurements) and optical properties of the material used (for optical interferometric PTR measurements) as well as a new measurement process for measuring the relative recession of the device with respect to the surrounding shields/poles; (3) standard, new measurement process, or both for a head-performance-based approach to extract the PTR, in a manner similar to that used to extract overall head/tape.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Read Sensors in Magnetic Tape Systems

Submitter: Brent Reabe, Advanced Research Corporation

Technological Innovation at Stake: Computer-memory magnetic tape systems manufacturers are attempting to develop the next-generation magnetic tape systems that will attain the information storage capacities (areal densities) projected by the 2005 INSIC (Information Storage Industry Consortium) International Magnetic Tape Storage Roadmap. These systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

***Economic Significance of Innovation*:** The global data storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with tape drives having an annual volume of sales of hundreds of thousands per year with millions of magnetic tapes. Cost reductions due to improved production yields and increased benefit to users due to increased µconsumers and increased sales and profits for industrial firms.

***Technical Barrier to the Innovation*:** There is an inability to monitor and therefore control the width of the magnetic-resonance sensors of the read heads to the precision required for the next-generation magnetic tape systems in order to avoid track mis-registration by the read sensor.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The current method to measure the width of a read sensor is to estimate it by the output voltage of the sensor as it is scanned across a special micro-track written on a tape whose width is no more than one-quarter that of the sensor. The accuracy in the method is too low and too dependent upon control of too many variables associated with running tape over a head.

Potential Solutions to Measurement Problem: The need is for a dynamic and/or static method of precisely measuring the magnetic width of the read sensor in a laboratory setting. It is desirable for this measurement tool or system to also be capable of generating a sensitivity profile across the read sensor. It would be required to accommodate sensors ranging from 1µm to 50 µm in width, with resolution on the order of ten nanometers and accuracy on the order of one hundred nanometers.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Performance Characterization of Next Generation Magnetic Tape Systems

Submitter: Richard Dee, Sun Microsystems

Technological Innovation at Stake: Computer-memory magnetic tape systems manufacturers are attempting to develop the next-generation magnetic tape systems that will attain the information storage capacities (areal densities) projected by the 2005 INSIC (Information Storage Industry Consortium) International Magnetic Tape Storage Roadmap. These systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

***Economic Significance of Innovation*:** The global data storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with tape drives having an annual volume of sales of hundreds of thousands per year with millions of magnetic tapes. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

***Technical Barrier to the Innovation*:** The roadmap-projected areal densities of future-generation magnetic tape systems will require design tolerances that are beyond the current state of knowledge. In addition, new, superior instrumentation is required in order to achieve the requisite monitoring and control of the magnetic tape system production processes. The increases in areal densities have outpaced the ability to adequately characterize the individual effects on overall performance of the dimensions and behavior of head sensors, especially in multi-channel tape heads.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** There is no adequate measurement technique for the characterization in next-generation magnetic tape systems of track-to-track and head-to-head variations in: writing performance; read element output, distortion and stability; and cross-track sensitivity, including side reading and side/erase; and spacing loss function.

Potential Solutions to Measurement Problem: One potential solution is development of a standard reference tape that would allow effective elimination of variations in the medium being used as input source for the those in the head being characterized. A useful reference-standard magnetic would be a few meters in length and be uniform to a few percent variation in both the cross tape and down tape directions in the following parameters: magnetic moment thickness product; thickness of the magnetic coating; average roughness or some other measure of this to assure a uniform media contribution to the magnetic spacing; and low variation in magnetic grain/particle size to have a stable moment and noise properties.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Tape Asperities in Magnetic Tape Systems

Submitter: Anand Lakshmikumaran, Sun Microsystems; Larry Olson, Imation; Michael Sharrock, Imation

Technological Innovation at Stake: Computer-memory magnetic tape systems manufacturers are attempting to develop the next-generation magnetic tape systems that will attain the information storage capacities (areal densities) projected by the 2005 INSIC (Information Storage Industry Consortium) International Magnetic Tape Storage Roadmap. These systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

***Economic Significance of Innovation*:** The global data storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with tape drives having an annual volume of sales of hundreds of thousands per year with millions of magnetic tapes. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

***Technical Barrier to the Innovation*:** The roadmap-projected areal densities of future-generation magnetic tape systems will require design tolerances that are beyond the current state of knowledge. In addition, new, superior instrumentation is required in order to achieve the requisite monitoring and control of the magnetic tape system production processes. Next-generation magnetic tape systems require successive decreases in head-to-tape spacing. Of the five parameters of head-to-tape spacing, Compression of asperities of head surface is the barrier here.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** There is no effective and standardized method for measuring the parameter called "mean compressed tape asperity height", which is the compression of topographical high points, that is, the asperities, as the tape moves across the head and is a major contributor to the overall head-to-tape spacing. It is defined as the mean spacing between a contoured "smooth" glass head and a moving magnetic tape. This is currently measured using multi-wavelength interferometry, which requires knowledge of the optical properties of the tape and *in-situ* calibration to account for variations in internal reflections of glass, intensity of the light source, and ambient noise. All of which leads to inaccuracies of greater than 5 nm when an accuracy of less than 1.2 nm is required right now and < 0.4 nm will be required by 2015.

Potential Solutions to Measurement Problem: One possible solution is to have a "standard" cylindrical and/or flat glass head with steps ranging from 0.1 to a few nanometers. Static head-to-tape spacing could be measured using the tape of interest over this standard head and the interferometric system could then be calibrated accordingly. Care should be taken that the actual glass heads used for measurement have similar optical properties as the glass used in the standard head. This would be a dynamic measurement on a small sample of tapes but measurable over a number of locations along the length and width of tape. Since the measurement process is well defined, this may require a standard.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Temperature Profiles within Magnetic Tape Systems

Submitter: April Alstrin, Sun Microsystems

Technological Innovation at Stake: Computer-memory magnetic tape systems manufacturers are attempting to develop the next-generation magnetic tape systems that will attain the information storage capacities (areal densities) projected by the 2005 INSIC (Information Storage Industry Consortium) International Magnetic Tape Storage Roadmap. These systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

***Economic Significance of Innovation*:** The global data storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with tape drives having an annual volume of sales of hundreds of thousands per year with millions of magnetic tapes. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

***Technical Barrier to the Innovation*:** The roadmap-projected areal densities of future-generation magnetic tape systems will require design tolerances that are beyond the current state of knowledge. In addition, new, superior instrumentation is required in order to achieve the requisite monitoring and control of the magnetic tape system production processes. The absence of an experimental method available to characterize the temperature profiles within an operating magnetic tape impedes the ability to design and produce next-generation magnetic tape heads that manage the heat generated by the higher current densities associated with smaller sensor geometries.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Measuring the distribution of temperatures within the sensor of an operating magnetic tape head is the problem. Average temperature is monitored by measuring resistance. The distribution of temperatures is theoretically calculated based on modeling, often finite element analysis, which requires as input accurate values of many parameters, including the dimensions and geometry of each head component, head material properties, the current applied to the sensor, tape physical properties, tape velocity, head-tape contact area, and tape tension, most of which are difficult to determine.

Potential Solutions to Measurement Problem: An accurate, non-destructive, thermal-imaging method for measurement of temperature distribution within a tape head in static (tape stationary) and dynamic (tape moving) modes is needed. Two techniques are needed: one for bench level testing of heads without a tape transport system and another for probing the real operating environment of tape moving past a powered head.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Head-to-Tape Spacing in Magnetic Tape Systems

Submitter: Anand Lakshmikumaran, Sun Microsystems; Larry Olson, Imation; Michael Sharrock, Imation

Technological Innovation at Stake: Computer-memory magnetic tape systems manufacturers are attempting to develop the next-generation magnetic tape systems that will attain the information storage capacities (areal densities) projected by the 2005 INSIC (Information Storage Industry Consortium) International Magnetic Tape Storage Roadmap. These systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

***Economic Significance of Innovation*:** The global data storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large, and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with tape drives having an annual volume of sales of hundreds of thousands per year with millions of magnetic tapes. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

***Technical Barrier to the Innovation*:** The roadmap-projected areal densities of future-generation magnetic tape systems will require design tolerances that are beyond the current state of knowledge. In addition, new, superior instrumentation is required in order to achieve the requisite monitoring and control of the magnetic tape system production processes. Next-generation magnetic tape systems require successive decreases in head/tape spacing. There are five parameters of head-to-tape spacing, each of which needs to be measured and controlled beyond current capabilities.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** A technique used to measure Head-to-Tape Spacing is to extract a value of the head/tape spacing using a combination of functional performance and magnetic modeling. The accuracy of the prediction is dependent on the accuracy of the estimation of the parameters in the model as well as the validity of the assumptions in the model. Currently, it is expected that the accuracy of interferometric measurement is of the order of approximately 5 nm. Thus, if the total head-to-tape spacing is 50 or 60 nm, it is very difficult to get accurate numbers to within 5-6 nm. Reduction in overall head/tape spacing would require accuracies better than 2.5 nm by 2007 and accuracies better than 1 nm by 2015 for dynamic measurements at drive operating conditions of tape speed and tension.

Potential Solutions to Measurement Problem: One alternative is a standard reference tape with calibrated magnetic signal properties. By using a reference tape and precisely measuring the head PTR, head and tape components of spacing can be separated. Another alternative is to have a standard read head used to measure output from a reference tape recorded by the head to be measured. This would provide head/tape separation with respect to a recording (write) device. In both cases, magnetic modeling and high accuracy of other parameters used in the modeling might be required. Another alternative is the use of multi-wavelength interferometry to measure the mean separation between an actual recording head and a clear tape. Overall, these might require both new measurement process and standards.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Track Width in Magnetic Tape Systems

Submitter: Brent Reabe, Advanced Research Corporation

Technological Innovation at Stake: Computer-memory magnetic tape systems manufacturers are attempting to develop the next-generation magnetic tape systems that will attain the information storage capacities (areal densities) projected by the 2005 INSIC (Information Storage Industry Consortium) International Magnetic Tape Storage Roadmap. These systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

***Economic Significance of Innovation*:** The global data storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large, and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with tape drives having an annual volume of sales of hundreds of thousands per year with millions of magnetic tapes. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

***Technical Barrier to the Innovation*:** The roadmap-projected areal densities of future-generation magnetic tape systems will require design tolerances that are beyond the current state of knowledge. In addition, new, superior instrumentation is required in order to achieve the requisite monitoring and control of the magnetic tape system production processes. Increased areal densities require decreased track widths and increased risks of overwriting adjacent tracks unless track widths are precisely maintained..

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The measurement technique that industry is currently using to measure the write width of write heads is to measure the written width of the magnetic tracks as written on tape. The measuring device, Magnetic Force Microscopy (MFM), lacks the necessary resolution, is too slow, and is dependent upon a reference tape with variations of its own for comparability of results.

Potential Solutions to Measurement Problem: Solutions to the problem would be a standardized method that might be based on: (1) improvement in the MFM imaging method; (2) development of a Kerr imaging method; or (3) some unknown method. The solution should be capable of doing 2D or 3D measurement of the magnetic field measurement at the face of the write head in a few seconds (for 2D) or up to one minute (for 3D) with a resolution of 50 nm.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Computer Optical Disks for Data Archiving

Submitter: Barry H. Schechtman, Kristin A. M. Scott, Plasmon, Inc.

Technological Innovation at Stake: Next-generation computer optical disk data storage systems with improved capability to reliably store and retrieve critical information for large and small enterprises, industry, academia, government, and individual use, at any time, up to decades in the future.

***Economic Significance of Innovation*:** The global disk storage market is $60B. The U.S. share is ~ 40%. The data storage industry is large and is significant for how it improves all other segments of the U.S. economy. Archiving of data as record-keeping is critical to the operation of business, finance, government, private households and personal lives. It is also a regulatory requirement in many instances, such as to maintain compliance with HIPAA (Health Insurance Portability and Accountability Act). It is difficult to quantify the cost of not having reliable archiving, but it is surely in the tens of billions of dollars or greater; the loss of such capability will cause inability of many of society's activities to function. Entire organizations will find it difficult to operate without reliable access to archived data.

***Technical Barrier to the Innovation*:** Development of next-generation optical disk data storage systems that have the ability to maintain readability of archived data written decades earlier requires an understanding of the mechanisms of degradation in drive systems that is beyond current scientific and engineering knowledge.

***Stage of Innovation Where Barrier Appears*:** Marketing, R&D

***Measurement-Problem Part of Technical Barrier*:** Measurement techniques for accurately measuring the change in the readability of data stored on computer optical disks, as well as methodologies for measuring reliability of overall system performance in storage and retrieval have not been fully developed. In their absence, methodologies for assessing lifetimes are chosen by the manufacturer and are dependent on assumptions about media degradation processes (which are not very well characterized) and on extrapolations (that may not be appropriate) from test conditions to use conditions. Little public consideration has been given in the past to assessing the lifetime limitations of the drive technologies required to retrieve the data from the media. Methodologies to do this for the industry at large are yet to be defined.

Potential Solutions to Measurement Problem: Developers, manufacturers, and ultimately those who procure and use computer optical disk data storage systems need methods and standards for accurately measuring readability over extended periods of data stored on optical disk. Simpler metrics would include system throughput on a standard workload and block error rate in reading archival data. More sophisticated metrics that could be useful as precursors and early warning signals of the loss of ability to retrieve archived data would be a future refinement of the solution.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** Flexible Electronics: Electronic Structure at Critical Interfaces

***Submitter*:** DJ Gundlach, CA Richter, D Delongchamp, LJ Richter, MA Schen

***Technological Innovation at Stake*:** The development of large-area, flexible devices that revolutionize integrated circuits through new applications that take advantage of low-cost, high volume manufacturing, nontraditional substrates, nanoscale materials and processes, and designed functionality.

***Economic Significance of Innovation*:** New, disruptive electronics manufacturing technologies are under development that could lead to new to the world electronic and optical products such as printable large-area displays, wearable electronics, paper-like electronic newspapers, low-cost photovoltaic cells, embedded intelligence and ubiquitous sensors, and item level radio-frequency identification (RFID) tags. Market estimates range from $10-30 B globally by 2010-2015, with applications in displays, logic, and lighting. Organic light emitting diodes for displays and lighting represent the first products, projected to grow from approximately $0.5 B today to $3 B in 2010. Market expansions to $250 B by 2025 have been estimated should major technology and business barriers be overcome.

***Technical Barrier to the Innovation*:** Device performance is insufficient for many intended applications and cannot be predicted due to the lack of information and scientific understanding of the electronic structure of flexible electronic devices. Device electrical characteristics are dependent upon the electronic structure at the interfaces between the semiconductor and gate dielectric or the active material and the electrodes. The interfacial structure may not necessarily reflect the intrinsic properties of the constituent materials. The fundamental lack knowledge concerning the mechanisms controlling charge transfer, its impact of optical properties and characteristics in these materials hinders the development of the predictive theories and models necessary to improve device performance.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The electronic structure of the constituent interfaces comprising electronic devices, notably the density and distribution in energy of stable and metastable electrically active traps, plays a critical role in determining device electrical characteristics. Challenges in determining the electronic structure of critical interfaces include: unambiguously separating the contributions to the extrinsic device behavior of multiple device interfaces and the lack of physical models accurately describing the device operation when stimulated electrically and optically.

***Potential Solutions to Measurement Problem*:** The development of characterization methods (such as combinations of optical spectroscopy and electrical measurements) may provide determination of the electronic structure of critical device interfaces and help validate predictive models. Standard methods and models could be developed to inform researchers about electrically active traps created during device processing and biasing which would allow device performance to be improved.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Flexible Electronics: Materials-Device Correlation

***Submitter*:** EK Lin, DM DeLongchamp, DJ Gundlach, LJ Richter, MA Schen

***Technological Innovation at Stake*:** The development of large-area, flexible devices that revolutionize integrated circuits through new applications that take advantage of low-cost, high volume manufacturing, nontraditional substrates, nanoscale materials and processes, and designed functionality.

***Economic Significance of Innovation*:** New, disruptive electronics manufacturing technologies are under development that could lead to new to the world electronic and optical products such as printable large-area displays, wearable electronics, paper-like electronic newspapers, low-cost photovoltaic cells, embedded intelligence and ubiquitous sensors, and item level radio-frequency identification (RFID) tags. Market estimates range from $10-30 B globally by 2010-2015, with applications in displays, logic, and lighting. Organic light emitting diodes for displays and lighting represent the first products, potentially growing from approximately $0.5 B today to $3 B in 2010. Market expansions to $250 B by 2025 have been estimated should major technology and business barriers be overcome.

***Technical Barrier to the Innovation*:** The lack of meaningful correlations between device performance and the structure, properties, and chemistry of the critical interfaces. This is a difficult problem because the performance of the devices is determined by the structure of the materials within (1 to 2) nm of the interfaces and the wide range of potential materials that may be used. Additionally, basic knowledge of the mechanisms governing charge separation, transport, and loss is completely lacking at these length scales. Without this knowledge and correlations it is difficult for companies to innovate their products and for the industry to develop meaningful standard test methods for materials and devices.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Identifying the contributions to performance variations by specific materials and processing methods requires integrated metrology spanning multiple disciplines: device physics, material electronic structure, chemistry, and materials science. In particular, non-destructive methods for the molecular scale characterization of the interfaces of both model and complete devices (multiple ~ 100 nm layers on an organic (flexible) substrate with complete encapsulation) are currently inadequate. Available techniques lack sufficient depth resolution, chemical resolution (the components are often chemically similar and thus difficult to distinguish) and sensitivity.

***Potential Solutions to Measurement Problem*:** The development of non-destructive, depth-profiling techniques with nanoscale spatial resolution and the ability to distinguish chemically similar molecular defects. Available techniques include soft x-ray synchrotron spectroscopy, neutron and x-ray reflectometry, and non-linear optical and dielectric spectroscopy. Standard test methods could be developed to inform researchers and product developer about specific problems within the materials or processing methods and serve as a common platform between parties.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Flexible Electronics: Device Parameterization

***Submitter*:** DJ Gundlach, JS Suehle, EK Lin , LJ Richter , MA Schen

***Technological Innovation at Stake*:** The development of large-area, flexible devices that revolutionize integrated circuits through new applications that take advantage of low-cost, high volume manufacturing, nontraditional substrates, nanoscale materials and processes, and designed functionality.

***Economic Significance of Innovation*:** New, disruptive electronics manufacturing technologies are under development that could lead to new to the world electronic and optical products such as printable large-area displays, wearable electronics, paper-like electronic newspapers, low-cost photovoltaic cells, embedded intelligence and ubiquitous sensors, and item level radio-frequency identification (RFID) tags. Market estimates range from $10-30 B globally by 2010-2015, with applications in displays, logic, and lighting. Organic light emitting diodes for displays and lighting represent the first products, potentially growing from approximately $0.5 B today to $3 B in 2010. Market expansions to $250 B by 2025 have been estimated should major technology and business barriers be overcome.

***Technical Barrier to the Innovation*:** The parameters reported for device performance in flexible electronics vary widely even with nominally the same materials and device structure. These problems arise because diverse measurement methodology and inaccurate device models are employed which make key device parameters poorly defined and of limited use as figures of merit. As a result, it becomes difficult to make systematic improvements in device performance and to establish specifications of materials, processes, or functional circuits.

***Stage of Innovation Where Barrier Appears*:** R&D, Production

***Measurement-Problem Part of Technical Barrier*:** Poorly defined electrical test methods are used and device parameters such as mobility are derived using relationships for ideal crystalline semiconductor devices. More precise models and unambiguously defined electrical test methodology are needed to more accurately and reproducibly determine key parameters specific to devices for flexible electronics.

***Potential Solutions to Measurement Problem*:** The development of well-defined electrical characterization methods and analysis protocols would permit device parameters serving as key figures of merit to be accurately defined. The development of appropriate test structures and accurate models are needed to disentangle parasitic effects that cause deviations from ideal device behavior. Standard electrical test methods and models would aid researchers in interpreting results from their design of experiments, designing devices and circuits, and verifying findings from different laboratories.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Flexible Electronics: Reliability

***Submitter*:** C.A. Richter, J.S. Suehle, E.K. Lin , L.J. Richter, M.A. Schen

***Technological Innovation at Stake*:** The development of large-area, flexible devices that revolutionize integrated circuits through new applications that take advantage of low-cost, high volume manufacturing, nontraditional substrates, nanoscale materials and processes, and designed functionality. Device reliability and lifetime are hurdles yet to be overcome in the development of flexible electronic devices.

***Economic Significance of Innovation*:** New, disruptive electronics manufacturing technologies are under development that could lead to a new class of electronic and optical products that will significantly displace current technologies used for similar purposes. Such may be printable large-area displays, wearable electronics, paper-like electronic newspapers, low-cost photovoltaic cells, embedded intelligence and ubiquitous sensors, and item level radio-frequency identification (RFID) tags. Market estimates range from $10-30 B globally by 2010-2015, with applications in displays, logic, and lighting. Organic light emitting diodes for displays and lighting represent the first products, growing from approximately $0.5 B today to $3 B in 2010. Market expansions to $250 B by 2025 have been estimated should major technology and business barriers be overcome.

***Technical Barrier to the Innovation*:** The wide use and market penetration of emerging flexible electronic devices is limited by the stability and life-time of these new structures. The physical mechanisms controlling long-term device reliability are largely unknown. In other cases such as the brightness of organic light emitting diodes, the devices cannot operate at their optimal performance levels without dramatically decreasing their lifetime. For novel flexible electronics to be brought to market the product lifetime must be established and meet current consumer expectations of several years of useful life. Accelerated testing techniques and models for projecting device lifetime are needed and are not available.

***Stage of Innovation Where Barrier Appears*:** R&D, End Use

***Measurement-Problem Part of Technical Barrier*:** The scientific principles and mechanisms describing device operation on flexible substrates and in organic materials are not fully known. Without this knowledge (such as the correct physical models, failure statistics, and acceleration parameters for temperature, humidity, bias, and mechanical stress), the development of accelerated life test protocols to accurately predict device lifetimes will be difficult. A sufficient understanding of defect generation, bias and temperature induced instabilities, wear-out, and breakdown is required to develop new reliability testing and lifetime projection methodologies. New measurements are needed to expand the science base needed for reliable flexible electronic devices, e.g., quantitation of material degradation or dielectric breakdown voltages.

***Potential Solutions to Measurement Problem*:** The development of accelerated testing methods, accompanying degradation models, and analysis protocols to quickly and accurately predict product lifetime for a variety of flexible electronic devices and applications. Standard test methods could be developed to inform and aid researchers and product developers to characterize specific reliability problems within the materials or processing methods and serve as a common platform between parties.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Flexible Electronics: High Volume Manufacturing

***Submitter*:** LJ Richter, MA Schen, EK Lin, DJ Gundlach

***Technological Innovation at Stake*:** The development of large-area, flexible devices that revolutionize integrated circuits through new applications that take advantage of low-cost, high volume manufacturing, nontraditional substrates, nanoscale materials and processes, and designed functionality.

***Economic Significance of Innovation*:** New, disruptive electronics manufacturing technologies are under development that could lead to new to the world electronic and optical products such as printable large-area displays, wearable electronics, paper-like electronic newspapers, low-cost photovoltaic cells, embedded intelligence and ubiquitous sensors, and item level radio-frequency identification (RFID) tags. Market estimates range from $10-30 B globally by 2010-2015, with applications in displays, logic, and lighting. Organic light emitting diodes for displays and lighting represent the first products, growing from approximately $0.5 B today to $3 B in 2010. Market expansions to $250 B by 2025 have been estimated should major technology and business barriers be overcome.

***Technical Barrier to the Innovation*:** The complete lack of adequate inspection tools for quantities such as defects, device tests, or substrate dimensional stability needed to enable real-time process control and to assure product quality inhibits commercialization. Roll to roll (R2R) printing and other high-volume manufacturing methods will operate at least 10 times faster than conventional panel to panel processes, allowing for the production of lower cost devices, but requiring revolutionary advances in inspection tools.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** New concepts in nanotechnology, fluidic assembly, and roll-to-roll processing are being leveraged to create low temperature manufacturing solutions. These disparate technologies create measurement barriers during manufacture that are dependent upon the unique processes employed and the revolutionary products being developed. High speed defect detection, functional testing, and R2R web characterization challenge instrumentation and informatics.

***Potential Solutions to Measurement Problem*:** The diversity of manufacturing approaches requires the introduction of standards simply to properly identify the parameters to measure. The extreme production speeds needed to realize lower cost devices require new informatics tools and statistical quality descriptions. Breakthrough measurements for high speed inspection are needed, possibly by advancements in optical sensing, image recognition, and image processing solutions. On and off-line functional testing of circuits and patterns might be solved by advancements in optical sensing and electrical probing techniques.

***Technology at Issue*:** Flexible Electronics: High Speed Interconnects

***Submitter*:** J Obrzut, DJ Gundlach, LJ Richter, MA Schen

***Technological Innovation at Stake*:** The development of large-area, flexible devices that revolutionize integrated circuits through new applications that take advantage of low-cost, high volume manufacturing, nontraditional substrates, nanoscale materials and processes, and designed functionality.

***Economic Significance of Innovation*:** Printable large-area displays, wearable electronics, paper-like electronic newspapers, low-cost photovoltaic cells, embedded intelligence and ubiquitous sensors, and item level radio-frequency identification (RFID) tags, are new disruptive electronics manufacturing technologies. Market estimates range from $10-30 B globally by 2010-2015, with applications in displays, logic, and lighting. Organic light emitting diodes for displays and lighting represent the first products, potentially growing from approximately $0.5 B today to $3 B in 2010. Market expansions to $250 B by 2025 have been estimated should major technology and business barriers be overcome.

***Technical Barrier to the Innovation*:** New, thin printable materials with high conductivity are needed to form the electrical interconnects (wiring) transferring electromagnetic signals at microwave frequencies. At higher, several GHz, frequencies flexible interconnects have been shown to be more susceptible to degradation over a several year lifespan. Current technology utilizes materials that are not sufficiently flexible and require high temperature processing incompatible with the organic materials of flexible substrates.

***Stage of Innovation Where Barrier Appears*:** R&D, Production

***Measurement-Problem Part of Technical Barrier*:** Currently, the materials and measurements at DC or low frequencies, inadequate to advance this technology, are used. High frequency (microwave) measurements methods are needed and are not available. This makes it difficult to develop, test, and innovate products and for the industry to develop meaningful standard test methods for printable interconnect materials. Improved high frequency measurements will enable better characterization of new nanostructured-materials and develop fundamental models for understanding the structure-property relations.

***Potential Solutions to Measurement Problem*:** The development of non-destructive measurement techniques that address the relevant materials structure and the corresponding functional high frequency electromagnetic properties. New microwave techniques that address signal propagation and non-linear dielectric effects in thin films. Standard test methods that inform researchers and product developers about specific problems within the materials or processing methods and serve as a common platform between parties are needed.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Flexible Electronics: Barrier Layers

***Submitter*:** E.K. Lin, L.J. Richter, D.J. Gundlach, M.A. Schen

***Technological Innovation at Stake*:** The development of large-area, flexible devices that revolutionize integrated circuits through new applications that take advantage of low-cost, high volume manufacturing, nontraditional substrates, nanoscale materials and processes, and designed functionality.

***Economic Significance of Innovation*:** New, disruptive electronics manufacturing technologies are under development that could lead to new to the world electronic and optical products such as printable large-area displays, wearable electronics, paper-like electronic newspapers, low-cost photovoltaic cells, embedded intelligence and ubiquitous sensors, and item level radio-frequency identification (RFID) tags. Market estimates range from $10-30 B globally by 2010-2015, with applications in displays, logic, and lighting. Organic light emitting diodes for displays and lighting represent the first products, growing from approximately $0.5 B today to $3 B in 2010. Market expansions to $250 B by 2025 have been estimated should major technology and business barriers be overcome.

***Technical Barrier to the Innovation*:** The accurate prediction of the lifetime of encapsulated, large-area, flexible electronics and photonics during operation in ambient environments. It is well known for organic displays that moisture and oxygen can degrade the performance of the devices through chemical reactions that alter the needed material properties. However, there are no methods to determine relevant permeation rates of contaminants so that accurate estimates of device lifetime and reliability can be established.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** There are no measurement methods that are sufficiently quantitative for the moisture permeation rate through barrier layers used to encapsulate large-area, flexible electronics and photonics devices. The estimated moisture permeation rates necessary for commercially viable device lifetimes are of the order of 10^{-5} g/m^2/day. Infrared spectroscopy measurements are not sufficiently sensitive and a recently developed calcium test is not sufficiently quantitative.

***Potential Solutions to Measurement Problem*:** X-ray reflectometry can measure film thickness changes on the order of Angstroms. By measuring thickness changes in barrier layer films as a function of temperature and humidity, permeation rates on the order of 10^{-6} g/m^2/day may be achieved. When combined with existing tests, these x-ray reflectivity measurements may provide a route towards benchmarking ultra low permeation rate constants.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Atomic-Precision Imaging to Aid in Development of New Materials

***Submitter*:** USMS MEMS/NEMS Group, D. T. Read

***Technological Innovation at Stake*:** Carbon-nanotube fiber-matrix composites is new form of material that promises to yield light-weight, ultra-high-strength components of a wide variety of products, from airplanes and satellites to flywheels for energy storage. Winning products will be the strongest and lightest, yielding high value for consumers and commanding premium prices for producers.

***Economic Significance of Innovation*:** The current world-wide market for high-performance fibers, reported by the National Materials Advisory Board of the National Research Council, is $400 million (38 million pounds of material at just over $10 per pound), leveraging successively the markets for the fiber-composites, fiber-matrix-based components, and ultra-high-strength products based on them.

***Technical Barrier to the Innovation*:** The extreme strength of carbon nanotubes points to fiber-matrix composite materials of great economic value. The key to optimum performance in a fiber-matrix composite material is the strength of the interface between the reinforcing fibers and the polymer matrix. Conventional methods developed for fabrication of fiber-matrix composites with larger, weaker fibers have not succeeded with the new ultra-fine, ultra-strong fibers. Proper dispersion of the fibers in the matrix is difficult and the fiber-matrix interface seems weak. Inability to know the atoms are in the as-manufactured material, how they move, and how they de-bond when the material is stressed impedes the ability to design fiber-matrix composites with adequately strong interfaces.

***Stage of Innovation Where Barrier Appears*:** Research and development.

***Measurement-Problem Part of Technical Barrier*:** Because the carbon-nanotube fibers are very fine, with diameters measured in tens of nanometers, conventional methods of relating the structure of the fiber-matrix interface to its strength are not sufficient to reveal the problems and point to solutions. The measurement problem is the inability to examine and debug the atomic-scale 3-dimensional structure of the nanotube-matrix interface. Conventional imaging, even by scanning electron microscopy (SEM) and atomic force microscopy (AFM) are insufficient to determine the exact structure of the interface and find out how its performance could be improved. Transmission electron microscopy (TEM) and scanned probe microscopy (SPM) are not well suited to this interface problem in non-crystalline materials.

***Potential Solutions to Measurement Problem*:** What is needed is an instrument for atomic-level imaging of the fiber-matrix interface with capability to detect the location and define the chemical identity of each atom in the interface. Promising is a new type of Nano-Electro-Mechanical (NEN) probe instrument with the capability to gradually erode a material surface and record the location and chemical identity of each atom as it is removed. The instrument looks capable looks like it could provide measurement data that could be compared with the intent of the design, for example, a chemical-bond diagram of the desired interface structure, and accelerate the development of commercially valuable high-performance materials.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue**:** Micro-/Nano-Technology

Submitter**:** MEMS/NEMS Group [Craig McGray]

Technological Innovation at Stake**:** Micro-Electro-Mechanical systems (MEMS) is new technology based upon techniques borrowed from the semiconductor industry that make possible devices and machines like gears, motors, and springs so small their dimensions are best measured in millionths of a meter. MEMS devices are already commercial successes as accelerometers for automobile airbags, nozzles for ink jet printers; and projectors for high-end video displays. MEMS is forecast to produce a second semiconductor revolution that will drive growth in the U.S. economy for decades to come.

Economic Significance of Innovation**:** The market in MEMS technology is currently valued at over $5 billion and is estimated to be growing at an annualized rate of 17%. This market has much in common with the $ 200 billion integrated circuit (IC) industry, being comparable in size and growth at the present time to that of that industry in the 1980's.

Technical Barrier to the Innovation There is inadequate technical knowledge and information existing to allow the MEMS industry to implement what is called the "fab-less" method of development and design of commercial MEMS devices that has been the basis for success in the IC industry. A fabrication facility is hugely expensive and iterations in manufacture of various prototype devices to achieve device performance and process yield is time consuming and costly. The fab-less alternative relies on sophisticated mathematical-computational modeling of devices and processes. These simulations, in turn, rely on the presence of a full characterization of the fabrication process to be used. While MEMS are fabricated by processes used and characterized for fabrication of ICs, those processes have not been adequately for MEMS which depend on the interaction of phenomena from a much larger set of physical domains (including electrical, mechanical, thermal, optical, fluidic, and others).

Stage of Innovation Where Barrier Appears**:** R&D

Measurement-Problem Part of Technical Barrier**:** There is insufficient measurement data and the measurement methods to generate that data to adequately characterize a MEMS devices and their dependence on fabrication processes. Accurate data is needed for a large suite of material properties to be measured quickly within the manufacturing line, and at multiple locations across each wafer upon which multiple MEMS are fabricated, including:

Young's Modulus	Stress Gradient	Thermal Coefs.	Microstructure	Damping
Poisson's Ratio	Contamination	Surface Charge	Residual Stress	Density
Stiction	Fatigue/Creep	Bond Strength	Surface Roughness	Sidewall Angle

Potential Solutions to Measurement Problem**:** Direct measurement techniques for thin-film material properties; Compact models to calculate material properties from indirect measurements; Variation studies of material properties due to process parameters; Standard reference materials for film properties.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** MEMS

***Submitter*:** USMS MEMS/NEMS Group, D. T. Read

***Technological Innovation at Stake*:** Micro-Electro-Mechanical System (MEMS) are a new technology for switching of radio-frequency (RF) signals is wireless telecommunications. These MEMS-RF switches will enable multi-band operation, with higher efficiency and lower cost than transistor switches, in a variety of wireless devices, such as multi-band handsets, that support a variety of wireless services, such as voice and computer communications.

***Economic Significance of Innovation*:** The market for RF MEMS in 2009 has been estimated at $1.1 billion, according to Jérémie Bouchaud and Henning Wicht of Wicht Technology Consulting reported in Microwave Engineering and elsewhere. This lags an earlier forecast from the same source, which had predicted a market of $1 billion 2007. Technical barriers impeding market acceptance is considered to be one of the causes of this lag.

***Technical Barrier to the Innovation*:** MEMS RF switches, which open and close to an RF signal in response to a control voltage, while offering known technical and economic advantages in terms of performance vs price compared to alternative switching technologies in compact wireless device, have unknowns regarding reliability. The field reliability of such MEMS components is untested and there are no established methods for assuring field reliability. Devices of suspect reliability cannot be marketed profitably; reliability complaints that arise after a product is introduced can be costly. Unexplained deviations from expected service lifetime have been noted in reliability tests during the product development cycle. This issue threatens the viability of a significant family of products.

***Stage of Innovation Where Barrier Appears*:** Production

Measurement-Problem Part of Technical Barrier:There is presently no way to adequately measure the changes in surface chemistry, surface electrical charge, microstructure of the metal region the flexure elements that are suspected to contributors to early failure of MEMS RF switches.

***Potential Solutions to Measurement Problem*:** The solution has multiple parts: developing a practical understanding of the relationships between measurable material properties at the time of manufacture and in-service reliability of MEMS; development and fielding of advanced inspection tools for use in the production lines; and creation of a set of software to generate pass vs fail vs test further decisions based on inputs of quantitative material properties and quantitative inspection results.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Single biomolecule detection, classification, and measurement.

***Submitter*:** David Nesbitt, John Kasianowicz & Vincent Stanford (NIST)

Technological Innovation at Stake: Detecting and analyzing biomolecules at low concentrations, such as biowarfare toxins, products of pathogenic organisms, and pollutants.

***Economic Significance of Innovation*:** This technological innovation has potential to thwart acts of bioterrorism, enable a better understanding of fundamental processes in biology, and permit long-term monitoring of pollutants in the environment. Achieving this innovation would provide significant benefits to national health, defense, and security.

***Technical Barrier to the Innovation*:** Fundamental physical measurement and theoretical techniques are still rudimentary. For example, there is a lack of fluorescent probe molecules that do not photobleach or blink. Electrical measurements in this domain encounter fundamental physical limitations on the continuity assumptions of classical physics. New theories of fundamental measurement and statistical signal processing theory must be co-developed to open the domain to bioengineering applications.

Stage of Innovation Where Barrier Appears: R&D.

***Measurement-Problem Part of Technical Barrier*:** Existing methods have fundamental limitations: optical methods are currently limited to fluorescence measurements. Non-fluorescent optical methods are needed. Electrical and electronic methods can be limited by the small current flows and the discrete number of ions available in high bandwidth measurements. Advanced statistical algorithms are needed to address that issue.

***Potential Solutions to Measurement Problem*:** The Government must work with the nanobiotechnology research community to develop new methods and materials. Nanofabrication, a new suite of physical measurement technologies, and better theoretical methods will guide the development of measurement technology.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Rapid and Low-Cost DNA Sequencing

Submitter**:** John Kasianowicz & Vincent Stanford

Technological Innovation at Stake: Low-cost, and rapid sequencing of DNA without extensive amplification and sequence fragment reassembly that requires vast supercomputer processor arrays.

Economic Significance of Innovation**:** This technical innovation has potential for high payoff in individual genome sequencing for genetically tailored healthcare. For example, numerous antihypertensive medications have been shown to have sensitivity to ethnic and individual genetic variability. For example, if developed in conjunction with pharmaceuticals, doctors would be able to prescribe medicines with much greater efficacy and reduced side effects. Rapid, low cost DNA sequencing would also enable and stimulate research on genetic diversity and evolution of all organisms. This could facilitate large-scale screening of biological substances for pharmaceutical use.

Technical Barrier to the Innovation**:** The first human genome sequence cost approximately three billion dollars. In that case, the DNA was fragmented and massively replicated for analysis by gel electrophoresis. The sequenced fragments were computationally reassembled into the complete and ordered genome. The latter process required hundreds of advanced computer systems and considerable time. To avoid laborious DNA fragmentation, replication, sequencing, and computational reassembly, the ability to directly analyze single DNA molecules, without the need to pre-process the molecules, must be developed.

Stage of Innovation Where Barrier Appears: R&D.

Measurement-Problem Part of Technical Barrier**:** Currently, single molecule techniques include nanopore-based electronic measurements and direct confocal fluorescence measurements. Other techniques need to be developed, such as electronic tunneling across DNA molecules. Low-noise physical measurements and novel signal processing techniques will also be required to directly extract sequence information from single DNA molecules.

Potential Solutions to Measurement Problem**:** Collaboration between the government and the nanobiotechnology research community to develop methods and materials (natural and physical) that will enable new metrologies. It must also aid the development of advanced algorithms for signal classification, particularly including system state identification and decoding.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Advancing the Fundamental Science of Nanobiotechnological Systems

***Submitter*:** Michael J. Tarlov, John Kasianowicz (NIST)

***Technological Innovation at Stake*:** Nanobiotechnology (NBT) develops and applies tools and processes of molecular nanotechnology for the study of biological systems. It borrows concepts from biological systems to design either materials with novel and improved properties or nano/micro-devices that mimic living biological systems. Nanomedicine, a subset of NBT, will use the tools of molecular nanotechnology to diagnose, treat, and prevent disease; relieve pain; and improve human health. The development of NBT as a mature scientific and technological discipline will enable scientists to build synthetic biological devices, such as tiny sensors to scan for the presence of infectious agents or metabolic imbalances, and engineered nanoscale therapeutics to target and destroy infectious agents or fix "broken" parts in cells. NBT tools will be useful for a wide range of tissues and disease, not just for a single disease or particular type of cell.

***Economic Significance of Innovation*:** The potential of NBT are more efficient, cost-effective healthcare that will improve our quality of life. Many diseases such as cancer, diabetes, Alzheimer's and Parkinson's disease, cardiovascular problems, etc., are currently diagnosed at acute or chronic stages where treatments are expensive and not particularly effective. Advances in NBT are expected to lead to early diagnosis, smart treatments, and the triggering of self-healing mechanisms. Total US health expenditures, $1.7 trillion in 2003, are currently rising at 4 times the rate of inflation and represent 15.3% of the GDP.

***Technical Barrier to the Innovation*:** Full realization of NBT's potential requires more fundamental understanding of nanotechnology as it relates to biomedical applications. A central theme of NBT is exploiting novel and improved properties that emerge at the nanoscale. Knowledge of these properties will help scientists predict, develop, characterize, and control nanoscale hybrid structures for biomedical applications.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Progress in NBT requires biophysical and biochemical measurements, development of theoretical models, and experimental validation. One barrier is the ability to obtain pure, monodisperse materials for these measurements. Macroscopic measurements of ensembles of materials are often dominated by substituent's properties. Improved methods for purifying and separating samples are required. The development of non-invasive probes of single-particle NBT properties is also needed. Current computational models for NBT materials can only handle systems consisting of hundreds of atoms. More robust computational methods that can predict properties for thousands of atoms are needed.

***Potential Solutions to Measurement Problem*:** Improvements in spectroscopic methods and nanoscale probe tools are needed to measure the physical and chemical properties and biological activity of NBT systems. New nanoscale measurement tools will be used to improve the basic scientific understanding of self-assembly and biologically driven self-assembly to enable the design, fabrication, and characterization of novel NBT structures for biomedical applications. Improvements in the accuracy, reliability, and transferability of quantum chemical methods are required for predicting the chemical and physical properties of NBT systems and comparing experiment with theory. An improved understanding of separation mechanisms needs to be established to improve the purity of NBT samples for further probing of fundamental properties.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Verified and accurate nanoscale computer simulation tools

***Submitter*:** Vincent Stanford and John Kasianowicz (NIST)

***Technological Innovation at Stake*:** Fundamental ability to accurately model and predict the properties of materials structured at the nanoscale. The innovation is in research that will ultimately benefit commercial arts and engineering methods capable of modeling and analyzing nano-scale materials?

***Economic Significance of Innovation*:** This is a high technical risk and long-term research area with potential for high payoff in a family of fundamental nanobiotechnologies (e.g., pharmaceuticals, homeland security, aerospace, defense, automotive). The ability to produce materials structured at the nanoscale is crucial to many advanced materials and products. The physical properties of some nanomaterials (e.g., C60 compounds) can be extraordinary (e.g., very high tensile strength and electrical conductivity) and could enable to the development of advanced materials and products.

***Technical Barrier to the Innovation*:** Significant barriers to these innovations include a lack of computational models of objects at the nano, meso, and larger scales. There is currently a lack of standards in force field definition. For example, two leading models, the USC Assisted Model Building with Energy Refinement (AMBER) and the Chemistry at HARvard Macromolecular Mechanics (CHARMM) produce simulations that differ from each other and from experiment for the conformation of simple DNA molecules. Reconciling new nanometer-scale measurement technologies and computational models for nanomaterials is a key issue.

Stage of Innovation Where Barrier Appears: R&D.

***Measurement-Problem Part of Technical Barrier*:** Validation of Molecular Dynamics (MD) models requires measurement of single-molecules and of bulk properties related to single molecule state mixtures. Promising single molecule techniques include, nanopore electronic measurements, Raman Spectroscopy, Fluorescent Resonant Energy Transfer (FRET), and tracking of fluorescent particles in solution or on surfaces. Nuclear Magnetic Resonance could also provide spectroscopic confirmations of mixtures of conformation states of particular molecular species. MD models must be adapted to predict experimental results and be reconciled against actual experiments.

***Potential Solutions to Measurement Problem*:** The Government should work with the nanobiotechnology research community to understand how to decode information derived from single molecule measurements. Standards for nanoscale metrics and standard reference data must be provided to facilitate model development and evaluation.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: C60 Carbon Nanomaterials for Nanobiotechnology

Submitter**:** Angela Hight-Walker, John Kasianowicz, and Vincent Stanford

Technological Innovation at Stake: The ability to rationally fabricate C60-based structures at the nanometer-length scale could enable a wide variety of applications in nanobiotechnology.

Economic Significance of Innovation**:** This is a long-term research area with potential to revolutionize drug delivery and fundamental measurements at nanometer length scales. For example, encapsulation of pharmaceutical agents in C60 nanoscale spheres might reduce both the amount of a drug needed to reach the target tissue and toxicity to patients. C60-based nanomaterials might also be used for in vivo monitoring of cellular processes.

Technical Barrier to the Innovation**:** The barriers include synthesizing and purifying uniform nanomaterials (either synthesize uniform materials or develop the ability to separate the devices based on some criteria), characterizing the devices with physical methods, manipulating and packaging such small structures, interfacing nanoscale objects with mesoscopic measurement systems, and predicting theoretically the physical properties and performance of the nanoscale devices. Theoretical ab-initio calculations are relatively good but only to within a constant. Models and data correlate well, but the scale factor is not well determined.

Stage of Innovation Where Barrier Appears: R&D.

Measurement-Problem Part of Technical Barrier**:** Current C60 synthetic capabilities produce samples with wide distributions of geometry, diameter, length, and other properties. It would ultimately be helpful to produce uniform and pure C60 forms for commercial products and reference materials. Currently, there is a need to separate the heterogeneous batches that existing synthesis techniques yield.

Potential Solutions to Measurement Problem**:** Carbon nanotube breathing frequency correlates well with diameter. Absorption, and excitation both are important spectral techniques and can allow unseparated species to be measured and identified even in bulk. The government should work with the nanobiotechnology research community to develop methods and materials.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Single molecule optical measurement

***Submitter*:** Lori Goldner

***Technological Innovation at Stake*:** The ultimate limit of all nanobiotechnology is the ability to follow a bioreaction on a single molecule scale which requires optical detection and measurement of single molecules. This ability makes the optical detection and measurement of rare species possible and can revolutionize the basic understanding of biological and biochemical processes, thereby advancing the understanding of cellular activity and treatment of disease.

***Economic Significance of Innovation*:** The ability to make single molecule measurements eliminates the waste of expensive resources and reduces to a minimum the need to deal with harmful or toxic substances. Significant reductions in time and costs can be realized by using single molecule measurement techniques to replace laboratory processes that require amplification such as polymerase chain reaction (PCR). Reduction in costs and damage to the environment can be achieved by minimizing the use of expensive chemical reagents, which may pose significant health hazards when used in greater than trace quantities.

***Technical Barrier to the Innovation*:** Isolation, immobilization (when necessary), and chemical labeling of the species under investigation are the primary technical challenges facing industry regarding the use and reliability of single molecule measurements.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Nanoencapsulation and labeling schemes that are minimally perturbative to a single molecule or a single nanobiosystem such as a molecular complex, virus, or organelle are needed. A good nanoencapsulation system will not change the functionality of the molecule or nanobiosystem under test. Determining the magnitude or the degree of perturbation requires research into measurement methods and technologies.

***Potential Solutions to Measurement Problem*:** Nanoencapsulation schemes involving water-in-oil reverse emulsions and liposomes are possible and should be physically investigated. Current labeling schemes involve commercial dyes. New fluorescent species and analogs and optically detectable nanoparticles are alternatives that can increase sensitivity, therefore reducing the concentration of nanoparticles required. In some cases, comparison of single molecule and traditional bulk experiments can be used to investigate degree of perturbation and optimize single molecule technique. In other cases, direct investigation and modeling of single molecule dynamics can be used to validate these techniques.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue**:** Image Coding for Telemedicine

Submitter**:** Charles Fenimore and Richard Bakkalar

Technological Innovation at Stake**:** Real-time interactive video/audio teleconferencing (VTC) between a medical specialist and a remote patient relies on coding (compression) that may lower video quality.

Economic Significance of Innovation**:** The market for products and technologies used in the remote delivery of healthcare, from telemonitoring to telesurgery, is currently undergoing a good deal of industry acceptance. Telemedicine is being adopted by healthcare providers and third party payors at an increasing rate. There is a $243M U.S. market for telemedicine products and services. Further development of this market is dependent on coding technologies. The U.S. telemedicine market may reach $6.9B by 2007.

Technical Barrier to the Innovation**:** The technical barrier is the absence of objective measures of effectiveness to demonstration operational consistency, reliability and performance. Medical applications using video teleconferencing (VTC) vary significantly in form, function, network topology and system costs (mature technical systems range in cost from $150 to $50,000). Each application should establish a cost-benefit analysis to demonstrate and validate the clinical value of higher quality systems.

Stage of Innovation Where Barrier Appears**:** Marketplace

Measurement-Problem Part of Technical Barrier**:** The measurement problems are to develop and validate objective measures of medical effectiveness (performance) and quality of service at various bit rates and network traffic levels which requires research into determining the particular quality aspects needed for diagnostic health services.

Potential Solutions to Measurement Problem**:** Create medically meaningful calibration devices and test protocols for objective evaluation of VTC compression and network performance for medical applications. Two applications are suggested – telemental health interviews and surgical endoscopy with significantly different requirements for image quality, bandwidth, associated metadata, video and audio performance and archiving.

Case Study – Measurement Needs

***Technology at Issue*:** Remote image-based medical diagnostic tools

***Submitter*:** Wendy Davis

***Technological Innovation at Stake*:** The implementation of electronic diagnostic tools on images obtained remotely in a telemedicine situation will significantly reduce the time required for patients or clinicians to travel to perform diagnoses. The remote image-based diagnostic instruments will have the capability of determining if an image requires analysis by a clinician. If the image requires analysis, it would then be forwarded to an appropriate clinician (i.e. member of patient's HMO). These devices could be potentially be implemented at local department stores or pharmacies.

***Economic Significance of Innovation*:** The economic significance is the reduction of unnecessary doctor visits and, more importantly, the availability of easy and early access to diagnoses, which will enable early detection. Diseases detected early are less expensive to treat. Overall U.S. medical imaging equipment sales are expected to become an $8 billion market by 2009. Worldwide medical imaging equipment sales are expected to be $20 billion by 2009. (Business Opportunity Report: Medical Imaging. July 2005)

***Technical Barrier to the Innovation*:** A typical diagnostic tool obtains an image and compares it to a database of diseased images using sophisticated algorithms, tailored to the particular disease or device. A method of universally validating the accuracy of algorithms does not exist and image requirements are specific to each particular electronic diagnostic tool. Users often have limited or nonexistent knowledge of how such algorithms will work or what aspects of the image are important. Therefore, these electronic diagnostic tools cannot be implemented on images obtained via telemedicine.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The measurement problem is developing a database of standard disease images that represent the types, characteristics and stages of various diseases from healthy to end stage with well calibrated imagers. With a standard database of images, these algorithms can be developed and validated to interpret the remote images.

***Potential Solutions to Measurement Problem*:** The solution is to develop an imaging system that is reliable, calibrated and superior to the technology that is to be implemented for obtaining remote images. This system can be used to obtain the images to be included in the database of standard disease images. This database can then be used to develop and validate algorithms for analyzing the medical images obtained via telemedicine.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Telemedicine Electronic Health Records Interoperability Standards

***Submitter*:** Michael Schultz

***Technological Innovation at Stake*:** Digital and/or open collaboration tools with medical information systems and video telemedicine systems will remove the interoperability issues that currently exist between medical devices.

***Economic Significance of Innovation*:** Electronic Health System Records (EHRs) is an enabling technology for telemedicine. It is anticipated that there will be a $156B savings from adoption of electronic health records. Currently, the inconsistent implementation of standards reduces U.S. competitiveness in this industry and increases the costs of delivering medical care.

***Technical Barrier to the Innovation*:** The technical barrier is a lack of confidence in the adoption of open standards due to the lack of validation

***Stage of Innovation Where Barrier Appears*:** Marketplace.

***Measurement-Problem Part of Technical Barrier*:** The measurement barrier is developing an open architecture that has been validated. The validation involves developing standards of quality for different applications. For example, there has been a lack of research on the impact of various compression technologies on clinical efficacy and diagnostic accuracy. While it is clear that some clinical imaging applications can tolerate more motion artifacts than others, little research has been done in this area.

***Potential Solutions to Measurement Problem*:** Identify the appropriate existing standards, prioritize them, customize them, publish them, and market them. Fund research studies which compare compression techniques in at least three different clinical areas. Identify various incentives to encourage adoption. Create performance benchmark reference data sets to validate technical conformance to standards.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** Telemedicine display systems

***Submitter*:** Paul Boynton

***Technological Innovation at Stake*:** As telemedicine-based operations increase, there is a growing need to communicate and render image information across different information display systems. New medical diagnostic and imaging techniques have become available and new and improved display technologies have come into use. Diagnosticians in many areas have integrated new imaging devices into their practice, often without regard to fidelity issues. Routinely, physicians take images home with them for viewing remotely. Images are e-mailed to consulting physicians without regard to whether the displays on which they are viewed meet minimum performance standards.

***Economic Significance of Innovation*:** Telemedicine is becoming an integral part of health care services in several countries including the U.S., Canada, the UK, Italy, Germany, Japan, Greece, Norway and India. The acquisition forward and display system market is expected to grow by 15% over the next three years within the U.S., with the U.S. being the largest market share. The U.S. market for radiography displays is expected to be $0.9 B by 2009, and the overall U.S. medical imaging equipment sales are expected to become an $8 B market by 2009.

***Technical Barrier to the Innovation*:** The technical barrier is validating that the quality of the images during review whether locally or remotely.

***Stage of Innovation Where Barrier Appears*:** Marketplace

***Measurement-Problem Part of Technical Barrier*:** There are no robust, straightforward, and interoperable metrics, standards, procedures, and guidelines to assess, calibrate, and ensure the quality of the displayed image. The main reason these metrics and standards do not exist is because the critical features of the diagnostic image that need to be rendered on a display screen are not well understood. Diagnosticians and physicians have been trained to look at an image and see the medical issues. There is no generally accepted algorithm that can be followed to detect the medical issues.

***Potential Solutions to Measurement Problem*:** There needs to be a set of robust and simple methods, procedures, guidelines, and metrics that can be used for specific modalities and at varying levels of conformance requirements based on the requirements of diagnosticians and doctors. Test targets, such as color bars or charts, can be developed to compare and allow for calibration of the displays.

NIST National Measurement System Assessment

Case Study – Measurement Needs

***Technology at Issue*:** Telemedicine Imaging Systems

***Submitter*:** Paul Boynton

***Technological Innovation at Stake*:** Digital medical image acquisition systems are a crucial element in the deployment of telemedicine-based health care in the U.S. New medical diagnostic and imaging techniques based on digital technology are becoming available. Diagnosticians in many areas have integrated new digital medical imaging devices into their practice, and can electronically send medical images for second opinions; however, the quality of these systems is unknown.

***Economic Significance of Innovation*:** Telemedicine is becoming an integral part of health care services in several countries including the U.S., Canada, the U.K., Italy, Germany, Japan, Greece, Norway, and India. The acquisition, forward and display system market is expected to grow by 15% over the next three years within the U.S., with the U.S. being the largest market share. The U.S. market for picture archiving and communications (PACS) market is predicted to grow to $2.3 B by 2009. Overall U.S. medical imaging equipment sales are expected to become an $8 B market by 2009. Worldwide medical imaging equipment sales are expected to be $20 B by 2009.

***Technical Barrier to the Innovation*:** The technical barrier is validating that the quality of the medical images with respect to color and spatial fidelity issues meets the requirements of the clinician or technician. Clinicians, technicians and physicians have been trained to look at an image and make the appropriate medial diagnosis. A universally accepted algorithm is required to reliably detect the medical issues present.

***Stage of Innovation Where Barrier Appears*:** Marketplace

***Measurement-Problem Part of Technical Barrier*:** There are no robust, straightforward, and interoperable metrics, standards, procedures, and guidelines to assess, calibrate, and ensure the quality of the digital medical images. The main reason these metrics and standards do not exist is because the critical features of the diagnostic digital medical image are not well understood.

***Potential Solutions to Measurement Problem*:** (1) Standardized procedures, protocols and metrics for accurate use of digital acquisition systems, including interoperability standards. (2) An image quality scale, based on physical measurements, could be developed based on the medical community criteria, which includes color, intensity, hue, compression, transmission, and archival/retrieval system capabilities. (3) A set of standard images to validate digital acquisition performance.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** TeleMental Health Interactive Video via Internet Protocol

***Submitter*:** Paul Boynton and Brian Grady

***Technological Innovation at Stake*:** Telemental health services are being developed to address the chronic lack of mental health services and professionals in rural and remote regions of the U.S. Presently, pilot programs throughout the nation provide routine mental health related services via dedicated telecommunication systems. The potential exists for this mode of delivery to become an essential component of the mental health delivery system. Internet Protocol (IP) is the most promising and cost-effective network technology to provide real-time interactive video between mental health professionals and their patients.

***Economic Significance of Innovation*:** The growth of telemental health projects has increased dramatically across the U.S. Many individuals in need of specialized mental health services live in geographically remote areas. Providing care to these patients can impose tremendous financial, travel, or personnel burden. The use of IP transmission, significantly more cost-effective than Integrated Services Digital Network (ISDN), can help reduce costs and increase implementation of services. Overall U.S. medical imaging equipment sales are expected to become an $8B market by 2009. Worldwide medical imaging equipment sales are expected to be $20B by 2009.

***Technical Barrier to the Innovation*:** There are many variables involved in real-time videoconferencing image and audio quality, e.g. jitter buffer, end-to-end delay, encryption, audio frequency response and bandwidth; all which can degrade or disrupt the transmission and the clinical process. The critical variables and the level of control required to maintain a functional level is unknown.

***Stage of Innovation Where Barrier Appears*:** Marketplace

***Measurement-Problem Part of Technical Barrier*:** No metrics or methodologies exist for evaluating the impact of IP variables on transmission or diagnostic quality with respect to the telemental health delivery system. The sensitivity of key aspects that a mental health professional uses to characterize patients nonverbal responses must be measured against the IP variables.

***Potential Solutions to Measurement Problem*:** Develop standardized procedures, protocols, metrics, and tools for create reference parameters for direct patient care videoconferencing, which will have a greater need than traditional video conferencing. These tools should be based on network measurements and on actual doctor-patient scenarios to determine the sensitivity of the IP parameters.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Hard Disk Fly Height Testing

Submitter: Dale Egbert, Seagate Technology

Technological Innovation at Stake: Hard disk drive manufacturers are attempting to develop the next-generation computer hard disk drive systems (HDDs) that will attain the information storage capacities in terms of the Terabits-per-square-inch densities projected by the INSIC (Information Storage Industry Consortium) technology roadmap. These higher-capacity systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

***Economic Significance of Innovation*:** The global disk storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large, and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with hard disk drive shipments of more than 400 million units per year. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

***Technical Barrier to the Innovation*:** The roadmap-projected terabits-per-square-inch information densities of future-generation hard disc drives require device design tolerances that are beyond the state of knowledge and instrumentation needed for the levels of monitoring and control of the production processes needed to achieve them. Variations in fly height in hard disc drives is a major mechanism of unreliability and failure that increases with decreasing dimensions and tolerances required of next-generation systems.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** There is no standardized method and associated reference standards for accurately measuring the absolute spacing of the HDD magnetic head flying over the rotating media. The reference standards for thin-film measurements that exist today are not of the same materials as HDD flying head slider, having different grain structure, surface finish, flatness, and index of refraction, making them unsuitable. As the spacing in HDD decreases below 10nm, achievement of the required 10% tolerance makes the need for absolute calibration standard critical.

Potential Solutions to Measurement Problem: Needed are traceable reference standards of gas film thickness for calibration of fly height testers in the range below 10nm. The reference standard needs to be: made of materials that match those of the head slider and disc (typically a composite ceramic material such as alumina titanium carbide with a surface roughness between 5 and 10 Angstroms and glass, respectively); certified for operation over a temperature range of $21^{o} \pm 10^{o}$ C; and able to be used inside a commercially available flying height tester.

Case Study – Measurement Needs

Technology at Issue: Hard Disk Slider Roughness

Submitter: Bruno Marchon, Hitachi Global Storage Technologies

Technological Innovation at Stake: Hard disk drive manufacturers are attempting to develop the next-generation computer hard disk drive systems (HDDs) that will attain the information storage capacities in terms of the Terabits-per-square-inch densities projected by the INSIC (Information Storage Industry Consortium) technology roadmap. These higher-capacity systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

***Economic Significance of Innovation*:** The global disk storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large, and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with hard disk drive shipments of more than 400 million units per year. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

***Technical Barrier to the Innovation*:** The roadmap-projected terabits-per-square-inch information densities of future-generation hard disc drives require device design tolerances that are beyond the state of knowledge and instrumentation needed for the levels of monitoring and control of the production processes needed to achieve them. In today's disk drive technology, the read/write element must fly above a disk surface at a distance no higher than 10 nanometers; this distance will be required to decrease to 1-2 nanometers in the near future.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** There is no known roughness measurement technology that can deliver the precision and accuracy to better design the air bearing sliders for more reliable flying over disk surfaces. Roughness measurements that can span 8 orders of magnitude and with better than 0.01 nm accuracy are virtually impossible to achieve in one instrument package, even for laboratory use. For production support, such measurement capability also need be able to measure thousands of parts quickly and repeatable, that is, must be gauge capable.

Potential Solutions to Measurement Problem: There are no off-the-shelf instruments that cover the range of wavelengths needed. However, there are two major types of surface topography technologies today: Mechanical probe (stylus, AFM) and optical based (scattering/interferometers). The former have higher resolution (~nanometer in case of AFM) but low repeatability; the latter is fast but has low resolution, micrometers. UV, far UV, and soft X-Ray) interferometry or scattering might overcome the wavelength limitation.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Hard Disk Drive Archivability

Submitter: Deva Ramaswamy, Seagate Technology, and David A. Gobran, Imation Corporation

Technological Innovation at Stake: Hard disk drive manufacturers are attempting to develop the next-generation computer hard disk drive systems (HDDs) that will attain the information storage capacities in terms of the Terabits-per-square-inch densities projected by the INSIC (Information Storage Industry Consortium) technology roadmap. Long-term data retention, combined with on-demand retrieval, is extremely important for satisfying multiple regulatory compliance requirements. Ability to retrieve data on demand from an HDD is a significant driver to using HDD-based archiving solutions. Data retention for long periods using HDD-based solutions needs to be demonstrated.

***Economic Significance of Innovation*:** The global disk storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large, and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with hard disk drive shipments of more than 400 million units per year. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

***Technical Barrier to the Innovation*:** The primary barrier is the proprietary nature of workloads and usage patterns for each archival-level system. Long-term data retention and HDD-based drive reliability heavily depend on the usage model and drive workloads. As the usage pattern dictates the life of an HDD, it is important to develop a data set to show the link between these variables and long-term data retention reliability metrics. Also, HDD-based solutions are dependent on the system and application layer protocols that manage the reliability of the drives.

***Stage of Innovation Where Barrier Appears*:** Marketplace

***Measurement-Problem Part of Technical Barrier*:** Methodologies for assessing reliability, mean time between failures (MTBF) and annualized failure rate (AFR) for HDD products are based on model and large-scale test bed data that are proprietary to the company that generates that data. These test-beds employ certain workload pattern and usage models for predicting MTBF. These predictive data need to be extended to determine, say, 10-year HDD life. Appropriate metrics to track such long-term data retention life have not been clearly established. Failure modes that occur in HDD life within 5 years may have been well quantified, but extending this to 10- or 15-year timeframes has not been established or demonstrated.

Potential Solutions to Measurement Problem: Development of HDD lifetime testing methodologies for use in archival storage systems. Organization and support of studies characterizing the failure mechanisms to develop data retention model for an appropriate usage or workload in such systems.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Hard Disk Remanence-Thickness Product

Submitter: Gerardo Bertero, Komag

Technological Innovation at Stake: Hard disk drive manufacturers are attempting to develop the next-generation computer hard disk drive systems (HDDs) that will attain the information storage capacities in terms of the Terabits-per-square-inch densities projected by the INSIC technology roadmap. These higher-capacity systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

***Economic Significance of Innovation*:** The global disk storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large, and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with hard disk drive shipments of more than 400 million units per year. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

***Technical Barrier to the Innovation*:** Future-generation hard disk drives, with terabits-per-square-inch information densities, will require design tolerances that are beyond the current state of knowledge. In addition, new, superior instrumentation is required in order to achieve the requisite monitoring and control of the hard disk drive production processes. The remanence-thickness product (MrT) is an important bulk property of hard disk drive (HDD) recording media. The HDD industry needs disk-based MrT standards for perpendicular magnetic recording (PMR) applications. The assignment of MrT should be traceable to well recognized standards of magnetization. The assignment of a reference MrT value can also be complicated by time effects (especially if the film is not thermally stable). A further complication for perpendicular recording media is the soft underlayer (SUL), which is always present in real recording media.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** Specific issues that would need to be addresses by measurement solutions in the development of standards include: characterization of form-factor(s) or platform(s), characterization of film properties, characterization of SUL properties, assurance of reasonable spatial uniformity of film properties, characterization of protective layer(s), dynamic considerations (e.g., temporal stability of properties, thermal decay, etc.), and measurement/assignment of calibrated areas.

Potential Solutions to Measurement Problem: A reference artifact can be generated by a chain of measurements that extends back to a calibrated VSM. The process of generating standard artifact in this manner is susceptible to errors in the various steps. Therefore, a need for a common source of reliable MrT standards is required that has characterized the measurement issues listed in the previous section.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Hard Disk H_k Dispersion

Submitter: Gerardo Bertero, Komag

Technological Innovation at Stake: Hard disk drive manufacturers are attempting to develop the next-generation computer hard disk drive systems (HDDs) that will attain the information storage capacities in terms of the Terabits-per-square-inch densities projected by the INSIC (Information Storage Industry Consortium) technology roadmap. These higher-capacity systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

Economic Significance of Innovation**:** The global disk storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large, and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with hard disk drive shipments of more than 400 million units per year. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

Technical Barrier to the Innovation**:** Future-generation hard disk drives, with terabits-per-square-inch information densities, will require design tolerances that are beyond the current state of knowledge. In addition, new, superior instrumentation is required in order to achieve the requisite monitoring and control of the hard disk drive production processes. The development of a methodology for a fundamental measure of the magnitude dispersion in H_k and quantification of intergranular exchange in perpendicular media is required for research and development. In perpendicular magnetic recording (PMR), one of the most crucial properties defining the quality of a recording media is the intrinsic switching field distribution D(Hs) of the media grains. Thus, it is ultimately responsible for the achievable recording density.

Stage of Innovation Where Barrier Appears**:** R&D

Measurement-Problem Part of Technical Barrier**:** There is a crucial problem in materials characterization to devise methodologies that allow for a measurement of D(Hs) in magnetic media. The recording process is complicated by the fact, that D_I(Hs), i.e. the switching field distribution under the write head, is not simply a materials property, but it also depends on the surrounding magnetic structure, i.e. the specific bit pattern itself due to inter-granular interactions. Generally, such interaction aspects can be incorporated within realistic micromagnetic calculations of the recording process. This pathway of achieving a quantitatively accurate picture of the recording process, however, not only requires knowledge of the appropriate inter-granular coupling constants, but also the intrinsic switching field distribution D(Hs), which the media grains would exhibit if no interactions were present.

Potential Solutions to Measurement Problem: Various methodologies to characterize D(Hs) have been proposed and applied in the past, all of which have certain strengths and drawbacks. Investigation of new experimental approaches along with micromagnetic modeling is needed to develop a reliable measurement technique for research and development purposes.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Hard Disk Magnetic Dynamics

Submitter: Gerardo Bertero, Komag

Technological Innovation at Stake: Hard disk drive manufacturers are attempting to develop the next-generation computer hard disk drive systems (HDDs) that will attain the information storage capacities in terms of the Terabits-per-square-inch densities projected by the INSIC (Information Storage Industry Consortium) technology roadmap. These higher-capacity systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

Economic Significance of Innovation**:** The global disk storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large, and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with hard disk drive shipments of more than 400 million units per year. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

Technical Barrier to the Innovation**:** The media for perpendicular magnetic recording (PMR) is becoming more and more complex. The presence of the soft underlayers makes it necessary to measure the properties of and characterize the materials making up the media both independently and, what is even more important, in the final on-disk environment. Increases in density and bit rates will require measurement of the magnetization bit dynamics. With higher and higher bit rates, in the GHz range and higher, the matter of "damping" is also likely to become an important consideration. For "conventional" perpendicular media, it is likely that the damping is fairly large and only partially comprised of a component described by a Gilbert model. The fact that the "damping" in microwave magnetic materials is comprised of a wide variety of physical processes, most of which cannot be modeled in terms of a single Gilbert damping parameter, is an idea that appears not to be well known in the magnetic recording arena.

Stage of Innovation Where Barrier Appears**:** R&D

Measurement-Problem Part of Technical Barrier**:** It will be necessary to introduce novel metrology for high frequency permeability soft underlayers (SULs), for bit dynamics in media and to address the issues of the damping. At expected bit sizes of about 3 nm to 11 nm and with times that the write head needs to pass over the bit and potentially reverse it ranging from 130 ps to 600 ps, the investigation of bit dynamics in media will require implementation of experimental techniques with 100 ps time response for *in situ* media dynamics. The spatial resolution will have to be < 20 nm for perpendicular and particularly for patterned media. A lesser requirement of spin stand 300 nm spatial resolution and 500 ps time response is required for measurement of dynamic Hc and H_0.

Potential Solutions to Measurement Problem: Existing metrology has to be modified to address the specific issues in the media environment. The identification of the critical parameters and the development of common set of transfer standards and/or specific metrology tools for the emerging new materials need to be developed.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Hard Disk Remanence-Thickness Product

Submitter: Gerardo Bertero, Komag

Technological Innovation at Stake: Hard disk drive manufacturers are attempting to develop the next-generation computer hard disk drive systems (HDDs) that will attain the information storage capacities in terms of the Terabits-per-square-inch densities projected by the INSIC (Information Storage Industry Consortium) technology roadmap. These higher-capacity systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

***Economic Significance of Innovation*:** The global disk storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large, and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with hard disk drive shipments of more than 400 million units per year. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

***Technical Barrier to the Innovation*:** The dynamic coercivity or the switching field at short times is an important parameter that is being regularly monitored in the manufacturing of disk recording media. It provides a measure of the "writability" and "track width capability" of the media. At present, with longitudinal magnetic recording (LMR) media, the dynamic coercivity is estimated using a half-current technique on a spin-stand tester. Double-layer PMR media has a magnetically soft, highly permeable underlayer in addition to the magnetically hard recording layer. The soft underlayer (SUL) significantly increases the write field as it provides an efficient flux-path for a single-pole writer field. The SUL is separated from the recording layer by an intermediate layer which can be from 1 to 40 nm in thickness. The presence of the SUL makes application of the LMR measurement technique difficult, and PMR coercivity is currently measured at time scales significantly longer compared to the head write time. Coercivity vs. time is measured and short time coercivity can be estimated by extrapolation using Sharrock's formula. This approach takes too long and extrapolation is usually error prone even when assuming Sharrock's thermal-activation formula holds.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** A tool is needed to separate the effect of the SUL and intermediate layer such that the coercivity of the recording layer in the nanosecond time range can be determined and used for monitoring any variations in the film deposition process. The method should be quick and allow measurement on a full disk at any desired location on the surface.

Potential Solutions to Measurement Problem: A metrology tool is needed that is capable of time scale coercivity measurement at the ns level, capable of making measurements on a finished disk, and is nondestructive. The total measurement time for three locations on a disk needs to be < 5 min.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Hard Disk Photoresist Dimensional Measurement Tools

Submitter: Marcos Lederman, Western Digital Corporation

Technological Innovation at Stake: Hard disk drive manufacturers are attempting to develop the next-generation computer hard disk drive systems (HDDs) that will attain the information storage capacities in terms of the Terabits-per-square-inch densities projected by the INSIC (Information Storage Industry Consortium) technology roadmap. These higher-capacity systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

***Economic Significance of Innovation*:** The global disk storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large, and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with hard disk drive shipments of more than 400 million units per year. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

***Technical Barrier to the Innovation*:** Future-generation hard disk drives, with terabits-per-square-inch information densities, will require design tolerances that are beyond the current state of knowledge. In addition, new, superior instrumentation is required in order to achieve the requisite monitoring and control of the hard disk drive production processes. The reader and writer photoresist feature sizes and geometry are generally driven by the critical dimension requirements to meet disk drive areal density specifications. The INSIC HDD Roadmap shows reader and writer physical widths below 50nm in 2009 and below 30nm in 2013. At the present time, critical widths are in the 100nm – 150nm regime.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** For writer photoresist patterns, it is critical to characterize the three-dimensional profile, as the geometry of the structure varies significantly into the device. To enable high volume application, measurement throughput and cost per measurement are key. To ensure measurement accuracy, the fidelity of the photoresist structure must be maintained through the measurement. Measurement repeatability is essential and a nondestructive measurement is preferred. Additionally, automated metrology for various feature attributes, including sidewall angle, footing, line tilt, standing waves, undercut, line edge roughness and line width roughness is required. Several techniques currently in use for photoresist profile measurements have shortcomings making them unsuitable for high volume applications.

Potential Solutions to Measurement Problem: Possible approaches include: scanning electron microscopy (SEM) (including focused ion beam (FIB)-SEM and advanced imaging methods); CD-AFM; DUV Optical (immersion, advanced algorithms, shorter wavelengths); and/or scatterometry.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Hard Disk Sheet Magnetoresistive

Submitter: Marcos Lederman, Western Digital Corporation

Technological Innovation at Stake: Hard disk drive manufacturers are attempting to develop the next-generation computer hard disk drive systems (HDDs) that will attain the information storage capacities in terms of the Terabits-per-square-inch densities projected by the INSIC (Information Storage Industry Consortium) technology roadmap. These higher-capacity systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

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***Technical Barrier to the Innovation*:** Future-generation hard disk drives, with terabits-per-square-inch information densities, will require design tolerances that are beyond the current state of knowledge. In addition, new, superior instrumentation is required in order to achieve the requisite monitoring and control of the hard disk drive production processes. Current Perpendicular to Plane (CPP) magnetoresistive read sensors, such as Tunneling Magneto Resistance (TMR) sensors, used in newer-generation HDD magnetic heads, have substantially complicated the task of developing and monitoring the quality of sensor films. Contrary to earlier Current In Plane (CIP) sensors, were a simple 4-point resistance test would provide the MR coefficient and other essential film properties, the testing of these new sensors typically requires the fabrication of submicron-sized junctions, complete with lead and insulation layers. This time-consuming step is burdensome both at the development and production stage.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** The goal is to develop a magnetoresistive measurement capability on blanket (unpatterned) TMR and CPP GMR films, down to resistance area products (RA) of the order of 0.1 Ohm-μm^2, such as will be needed for the development and production control of CPP read head sensors in the coming years. A related, and more immediate, need is for such a technique to allow the measurement of today's TMR sensors films, directly on device wafers, without the need to deposit special purpose structures on witness wafers.

Potential Solutions to Measurement Problem: The groundbreaking introduction of the Current In Plane Tunneling (CIPT) technique by D. C. Worledge and P. L. Trouilloud , and its commercialization by Capres A/S in Denmark, have already provided blanket film metrology for TMR films with RA above 1 Ohm-μm^2. An extension of the CIPT technique seems the most likely approach to the desired 0.1 Ohm-μm^2 metrology capability.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Hard Disk Stack Metrology

Submitter: Marcos Lederman, Western Digital Corporation

Technological Innovation at Stake: Hard disk drive manufacturers are attempting to develop the next-generation computer hard disk drive systems (HDDs) that will attain the information storage capacities in terms of the Terabits-per-square-inch densities projected by the INSIC (Information Storage Industry Consortium) technology roadmap. These higher-capacity systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

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***Technical Barrier to the Innovation*:** Future-generation hard disk drives, with terabits-per-square-inch information densities, will require design tolerances that are beyond the current state of knowledge. In addition, new, superior instrumentation is required in order to achieve the requisite monitoring and control of the hard disk drive production processes. The traditional technique used for measuring metal stacks in magnetic head fabrication, X-Ray Fluorescence (XRF), is essentially a bulk spectroscopy that is unable to determine layer structure on even a qualitative basis. Because XRF essentially detects only atoms/unit area, without an independent control of density, it cannot be used to monitor layer thickness. Reader stacks are beginning to include lighter metals and thin dielectrics. The local chemistry of these layers will be important to map and to control especially for Current Perpendicular to Plane (CPP) topologies. XRF is not as sensitive to light elements as we would like and it has no ability to probe the bonding structure of dielectric materials. Because XRF is reliant on reference standards that in turn must be characterized by destructive mass spectrometry techniques, ultimate accuracy is difficult to ensure on a regular basis.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** A production-grade calibrated metrology tool that can provide precise microstructural and local electronic information about the content and structure of metal and buried dielectric stacks of films with, in some cases, repeated layers as thin as 1 nm.

Potential Solutions to Measurement Problem: Possible approaches worth exploring include XPS, SIMS, GDMS, XRR, Soft X-Ray Emission, and variable energy microprobe.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Hard Disk Thermal Mechanical Properties

Submitter: Marcos Lederman, Western Digital Corporation

Technological Innovation at Stake: Hard disk drive manufacturers are attempting to develop the next-generation computer hard disk drive systems (HDDs) that will attain the information storage capacities in terms of the Terabits-per-square-inch densities projected by the INSIC (Information Storage Industry Consortium) technology roadmap. These higher-capacity systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

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***Technical Barrier to the Innovation*:** Recording heads used in HDDs contain a wide variety of materials, including insulators, dielectrics, normal metals, ferromagnetic metals, and dirty metals. Many of these materials are patterned into structures ranging from several microns in lateral extent and ten to hundreds of nanometers thick, to structures tens to hundreds of nanometers in lateral extent and tens of nanometers thick. It important to understand the thermal and magnetic properties of such structures in order to control thermal expansion and temperature through the recording heads due to Joule heating.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** At present, thermal and mechanical properties of such patterned structures are poorly known, and there is a lack of standards and reliable (accurate and gage-capable) measurement techniques. In addition to measurements of single patterned structures, the transport properties are highly influenced by interfaces in heterostructures that often occur in recording heads. Therefore, there is a need not only to measure thermal and mechanical properties of single structures, but of heterostructures as well.

Potential Solutions to Measurement Problem: Develop standards, measurements techniques and tools to measure thermal conductivity, coefficient of thermal expansion, and Young's modulus applicable to sub-micron patterned elements and structures and heterostructures, as used in HDD magnetic heads. Thermal conductivity: One possible approach is picosecond thermoreflectance. However, the interpretation of these measurements is presently based on the one-dimensional diffusion equation, and its validity to patterned structures of limited lateral extent is not clear. Elastic moduli, Young's modulus: Current techniques are poorly developed for structures less than about 100 nm thick. A possible approach is picosecond ultrasonic measurements. Coefficient of thermal expansion: Develop or refine some existing method to measure thermal coefficient of expansion (in plane and out-of-plane) in thin films and thin film heterostructures. An initial approach in all three cases may be to focus on thin films and thin film heterostructures, and then extend these methods to patterned thin film structures.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Hard Disk Thermal Mechanical Properties

Submitter: Marcos Lederman, Western Digital Corporation

Technological Innovation at Stake: Hard disk drive manufacturers are attempting to develop the next-generation computer hard disk drive systems (HDDs) that will attain the information storage capacities in terms of the Terabits-per-square-inch densities projected by the INSIC (Information Storage Industry Consortium) technology roadmap. These higher-capacity systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

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***Technical Barrier to the Innovation*:** Future-generation hard disk drives, with terabits-per-square-inch information densities, will require design tolerances that are beyond the current state of knowledge. Scaling of the magnetic write head down to ever-smaller dimensions can fail at any time. Without a good understanding of the behavior of the magnetic field near the write pole, the obstacles to reducing the size could become insurmountable. Write field characterization, both spatially and temporally, will become critically important for the advancement of the areal density in the recording industry. For 1 $Tbit/in^2$ magnetic recording, the bit cell will be scaled to 38 nm wide by 15 nm long, and the data rate is estimated to be as high as 3 Gbits/sec. These dimensions, both spatially and temporally, exceed the industry's metrology capability. Alternative measurement techniques such as the Kerr-effect Magneto-Optical Microscopy, Magnetic Force Microscopy, and Magneto-resistance Sensitivity Mapping (MSM) have reached their accuracy limits as well.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** A good understanding of the magnetic behavior of the write head requires the ability to characterize the magnetic field with a spatial resolution that is only a fraction of the size of the pole (i.e. < 10 nm) and a temporal resolution that is only a fraction of the data-rate (i.e. < 100 ps)

Potential Solutions to Measurement Problem: Potential approaches worth investigating include improvements to: spin stand measurements techniques, contact read-write testers, magnetic force microscopy (MFM) techniques, semiconductor Hall probes, and giant magnetoresistive (GMR) sensors grown directly on an SUL.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Data Storage Archivability Testing

Submitter: David Peterson, Sun Microsystems, and James Goins, Imation Corp.

Technological Innovation at Stake: Computer-memory magnetic tape systems manufacturers are attempting to develop the next-generation magnetic tape systems that will attain the information storage capacities (areal densities) projected by the 2005 INSIC (Information Storage Industry Consortium) International Magnetic Tape Storage Roadmap. These systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

Economic Significance of Innovation**:** The global data storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large, and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with tape drives having an annual volume of sales of hundreds of thousands per year with millions of magnetic tapes. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

Technical Barrier to the Innovation**:** Lack of a scientific or sound empirical base for modeling and predicting the longevity and performance of magnetic tape relative to other types of data storage media, including magnetic disk, optical disk, and, holographic systems prior to actual media failure.

Stage of Innovation Where Barrier Appears**:** R&D

Measurement-Problem Part of Technical Barrier**:** Current accelerated aging protocols for the various formats are too disparate for easy comparison and no meaningful common metric solution is in sight. New standards and procedures are required.

Potential Solutions to Measurement Problem: There needs to be technically sound, standardized methods for accelerated-aging testing of the relative storage and retrieval capabilities of the various types of data storage media, including magnetic tape, magnetic disk, optical disk, and, holographic systems. There is a strong need to evolve a common metric and common approach for use by suppliers of each type of storage medium so that the performance of each can be meaningfully compared. Two possible metrics of relative performance are loss with time of magnetic remanence and increase with time of block error rates.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Imaging in Magnetic Tape Systems

Submitter: Guy Ruse, Quantum

Technological Innovation at Stake: Computer-memory magnetic tape systems manufacturers are attempting to develop the next-generation magnetic tape systems that will attain the information storage capacities (areal densities) projected by the 2005 INSIC (Information Storage Industry Consortium) International Magnetic Tape Storage Roadmap. These systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

Economic Significance of Innovation**:** The global data storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large, and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with tape drives having an annual volume of sales of hundreds of thousands per year with millions of magnetic tapes. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

Technical Barrier to the Innovation**:** The roadmap-projected areal densities of future-generation magnetic tape systems require device design tolerances that are beyond the state of knowledge and instrumentation needed for the levels of monitoring and control of the production processes needed to achieve them. Next-generation tape heads have more different types of exposed materials that are vulnerable to the reactive environment of the head-tape interface and present methods for imaging and characterizing the effects of such exposure are inadequate.

Stage of Innovation Where Barrier Appears**:** R&D and Production

Measurement-Problem Part of Technical Barrier**:** Present measurement methods are unable to adequately image and quantitatively characterize the change in magnetic performance of the thin film structures of a magnetic recording head at the tape bearing surface with the chemical and electrochemical degradation that occurs in manufacture and use. Methods are needed to evaluate the inevitable impact of exposure to energetically reactive environments for changes to (1) emanating magnetic fields, such as with write fields generated at pole tips or domain wall fields, such as associated with magnetic, grain or surface boundaries of MR sensors, MR shields or MR hard bias stabilizers; and (2) receptive magnetic materials in the reader structures, such as MRE, SAL, MR shields or MR hard bias stabilizers.

Potential Solutions to Measurement Problem: A key element of an effective solution to the measurement problem would be a chemical and structural micro-depth sensing magnetometer and the associated measurement method and reference standards to allow measurement the magnetic response of the recording head to chemical and structural changes within it near the sensing surface. The required measurement sensitivity is on the order of PPM at nanometer thicknesses over hundredths of squared microns of area.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Pulse Response Measurements in Magnetic Tape Systems

Submitter: Bill Rippard

Technological Innovation at Stake: Computer-memory magnetic tape systems manufacturers are attempting to develop the next-generation magnetic tape systems that will attain the information storage capacities (areal densities) projected by the 2005 INSIC (Information Storage Industry Consortium) International Magnetic Tape Storage Roadmap. These systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

***Economic Significance of Innovation*:** The global data storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large, and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with tape drives having an annual volume of sales of hundreds of thousands per year with millions of magnetic tapes. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

***Technical Barrier to the Innovation*:** The roadmap-projected areal densities of future-generation magnetic tape systems require device design tolerances that are beyond the state of knowledge and instrumentation needed for the levels of monitoring and control of the production processes needed to achieve them. There is insufficient understanding of the relationship of the magnetic response of a write head to the temporal shape of the input electrical pulse in the gigahertz range of frequency of the next-generation magnetic tape systems.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The high-frequency properties of magnetic material configured into the small structures of magnetic tape heads are presently not measurable. Pulsed inductive microwave magnetometers are not directly capable of measuring single-micrometer-size structures. Laser-based magnetic imaging systems do not have the required spatial resolution of 100. Scanned probe techniques do not have the frequency bandwidth. Modeling of the response of the structures to short current pulses is not accurately predictive.

Potential Solutions to Measurement Problem: Development of a measuring instrument system with the capability to measure the magnetic field generated by a write pulse in the write head of a magnetic tape drive for arbitrary input pulse forms with 100 nm spatial and sub-nanosecond temporal resolution. One possible solution may be based on the pulsed inductive microwave magnetometer developed at NIST. Other possible solutions are radical improvements in laser or scanned probe techniques.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Magnetostriction Measurements in Magnetic Tape Systems

Submitter: Dave Pappas, Michael Schneider

Technological Innovation at Stake: Computer-memory magnetic tape systems manufacturers are attempting to develop the next-generation magnetic tape systems that will attain the information storage capacities (areal densities) projected by the 2005 INSIC (Information Storage Industry Consortium) International Magnetic Tape Storage Roadmap. These systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

***Economic Significance of Innovation*:** The global data storage market is $60B. The U.S. share is approximately 40%. The data storage industry is large, and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50%. Magnetic data storage is a multi-billion-dollar industry with tape drives having an annual volume of sales of hundreds of thousands per year with millions of magnetic tapes. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

***Technical Barrier to the Innovation*:** The measurement of magnetostriction is an important aspect of new tape head development, including the shields, poles and sensors. The target value of magnetostriction for new materials is required to be as low as possible. Zero would be ideal, but in practice, magnetostriction should be measured and controlled to be in the $10^{-6} – 10^{-8}$ range. Deviations from this value could lead to undue stress, premature failure, or poor performance of tape heads. Current methods for which no physical standards exist cannot be implemented beyond the R&D phase.

***Stage of Innovation Where Barrier Appears*:** Production, R&D

***Measurement-Problem Part of Technical Barrier*:** Ideally, measurements on intact AlTiC wafers would aid greatly in the measurement of magnetostriction in a production facility as an auditing technique helping in quality control. In order to make this possible, a nondestructive, on-chip measurement needs to be developed. Current measurement methods involve either stressing or destroying the wafer in order to make a measurement. There is also no magnetostriction standard that can be used to calibrate the measurements systems. The current measurement systems are not absolute. This results in different "reference" samples at different facilities, none of which are traceable

Potential Solutions to Measurement Problem: A nondestructive, on-chip measurement method needs to be developed. A magnetostriction standard should be developed with a known value and a one part-per-billion accuracy. In addition to the standard for current measurement systems, it would be desirable to have a wafer-sized standard for future measurement systems. Ideally, standards would be available with different magnetostriction coefficients; $\lambda = \pm 1 \times 10^{-8}$, $\lambda = \pm 1 \times 10^{-7}$, and $\lambda = \pm 1 \times 10^{-6}$ being the most relevant.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Study Design for Proteomics Measurement Technologies

Submitter: Members of Executive Committee - USMS Measurement Challenges in Proteomics Workshop, 3/12/2006, Boston, MA

Technological Innovation at Stake: The ability to measure large numbers of proteins and protein fragments – proteomics - has the potential to speed discovery of biomarkers that are useful for studying pathologic mechanisms, for disease diagnosis, and for prognostication after disease onset. The scientific community has called into question the reproducibility and relevance of reported proteomics biomarkers and pointed to the absence of positive validation studies in the literature. The lack of good study design negatively impacts proteomics discovery efforts, resulting in the misidentification of markers or failure to detect markers.

Economic Significance of Innovation: In 2006, the number of deaths in the U.S. from cancer and heart disease is estimated to be nearly 1.5 million and treatment costs are estimated at over $475 billion. Properly designed proteomic studies have the potential to develop next-generation diagnostic and therapeutic treatments for these diseases that may reduce the cost of healthcare.

Technical Barrier to the Innovation: For proteomic biomedical science to advance, it is essential that research and clinical trial data be disseminated to the general public. However, there are circumstances when the results of research and clinical trials are often withheld from publication due to study results being found to be invalid. In many circumstances, this could be due to improper experimental set-up, collection of data, storage or shipping conditions of samples, lab error, etc. A lack of proper study design negatively impacts the growth potential of clinical proteomics. Poor study design leads to wasted effort, time, and creditability.

Stage of Innovation Where Barrier Appears: R&D

Measurement-Problem Part of Technical Barrier: No universal guidelines on proteomic measurement study designs are currently available or accepted by the community. Additionally, a lack of common data elements impedes development of a study design.

Potential Solutions to Measurement Problem: Solutions include the preparation of technical guides on study design issues for proteomics researchers that encompass recommendations for input from epidemiologists, biostatisticians and clinicians (at the design phase) and defined measures of compliance. Educational training in study design is also encouraged.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Proteomic-based Biomarker Discovery - Reference Materials

Submitter: Members of Executive Committee - USMS Measurement Challenges in Proteomics Workshop, 3/12/2006, Boston, MA

Technological Innovation at Stake: The success of proteomics to produce breakthroughs in clinical diagnostics, drug discovery, and fundamental biochemical and biomedical research is at stake until the measurement techniques used in proteomics can be made more reliable, reproducible, and their results validated through the use of reference materials. Improvements in proteomic research technologies cannot come until existing technologies have been validated.

Economic Significance of Innovation: If the current problems in proteomics, of widespread irreproducibility and lack of scientific validation of proteomic research results, continue to grow, it is likely that the confidence in the results of proteomics research will diminish. This will impact the future growth of this scientific discipline, economically and scientifically and stifle any chance that proteomics will produce any anticipated breakthroughs in medicine and clinical diagnostics. The major government funding agency for academic proteomic research, the National Institutes of Health, has recently limited one grant program in the types of proteomics measurement technologies that are applicable to funded research grant projects based on the lack of measurement validation of some proteomic technologies. If this trend continues, it will likely have a profound negative affect proteomic research in academia, including medical university research facilities, which rely on this support.

Technical Barrier to the Innovation: The advanced technologies used in proteomics, such as the electrophoretic and chromatographic separations and the mass spectrometric instrumentation for protein and peptide measurements have sufficient power to meet the needs for current proteomics research. however, lack of means to establish the comparability of results obtained by these tools is a barrier to their successful use to produce the discovery of new clinical biomarkers. Reliable and widely available reference materials are needed to standardize and validate proteomic research results.

Stage of Innovation Where Barrier Appears: R&D

Measurement-Problem Part of Technical Barrier: No widely accepted reference materials for proteomics exist which would allow for interlaboratory validation of research results and act as tools to aid in the understanding of the sources of bias and variation of proteomics research. Without the tools for evaluating existing proteomics technology, a barrier to the development of new or more advanced technology exists.

Potential Solutions to Measurement Problem: A variety of reference materials are needed for proteomics. These materials range from simple mixtures of purified and well-characterized proteins and peptides to well-characterized proteins in complex biological matrices such as serum, plasma, or tissue extracts. These reference materials need to provide both qualitative and quantitative information on their protein components. The stability of these materials is also critical and would need to be assessed and documented.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Affinity-Based Technologies for Protein/Peptide Measurement: Biomarker Assay Performance Characteristics

Submitter: Members of Executive Committee - USMS Measurement Challenges in Proteomics Workshop, 3/12/2006, Boston, MA

Technological Innovation at Stake: Protein chips have the potential to be an enabling technology for drug discovery and clinical proteomics. They can be used to identify and validate new drug targets, to develop improved understanding of molecular pathways, to facilitate the testing of potential therapeutic compounds, and to analyze the molecular signatures of disease.

Economic Significance of Innovation: Application areas for capture biochip assays in research include allergies, Alzheimer's disease, connective tissue disorders, autoimmunity, cancer, cardiovascular disease, inflammation, oncology, and immunoglobulin isotyping to name a few. The market potential of protein biochips is anticipated to grow to $500 million in 2008, once issues of reliability and versatility are overcome.

Technical Barrier to the Innovation: Robust protein chip assays must be validated for FDA Good Laboratory Practice compliance as a critical step to ensure that this technology platform's performance for sensitivity, specificity and reproducibility is consistent. The sources of data and the methodology to identify potential biomarkers, assay development and validation requirements to establish the performance characteristics of these methods and their migration to clinical trials are critical. Without performance characteristics, subjective judgments will lead to differences in acceptance of biomarkers and candidate surrogate endpoints. A lack of universal biomarker assay performance standards for affinity-based technologies negatively impacts the growth potential of protein chips from a research tool to a robust and reliable clinical tool.

Stage of Innovation Where Barrier Appears: R&D

Measurement-Problem Part of Technical Barrier: No biomarker assay performance standards exist for affinity-based multiplex assays (protein chips).

Potential Solutions to Measurement Problem: Solutions include the establishment of explicit performance standards for affinity-based multiplex (protein chip) assays. These include defining a method's analytical performance such as precision, linearity, parallelism, accuracy, dynamic range, interferences; an assay's minimum detectable concentration; an assay's lower limit and upper limit of quantitation; and a method's clinical performance such as range of normal values, specificity, and correlation with a reference method. Defining a population to be tested with proper end-points and intended use are also needed. The creation of expert panels consisting of clinicians, biostatisticians, technology experts and journal editors is warranted.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Affinity-Based Technologies for Protein/Peptide Measurement: Proficiency Testing Materials

Submitter: Members of Executive Committee - USMS Measurement Challenges in Proteomics Workshop, 3/12/2006, Boston, MA

Technological Innovation at Stake: Protein chips have the potential to be an enabling technology for drug discovery and clinical proteomics. A protein chip is a surface on which proteins or capture agents are immobilized. A key component of a protein chip system is surface chemistry, purified proteins, capture agents, and detection methods. They can be used to identify and validate new drug targets, to develop improved understanding of molecular pathways, to facilitate the testing of potential therapeutic compounds, and to analyze the molecular signatures of disease.

Economic Significance of Innovation: Application areas for capture biochip assays in research include allergies, Alzheimer's disease, connective tissue disorders, autoimmunity, cancer, cardiovascular disease, inflammation, oncology, and immunoglobulin isotyping to name a few. The market potential of protein biochips is anticipated to grow to $500 million in 2008, once issues of reliability and versatility are overcome.

Technical Barrier to the Innovation: Protein chips are used for the high-throughput study and identification of proteins. The main technical barriers are found in the lack of well-characterized, complex biological materials that can be used to measure the accuracy, sensitivity, dynamic range, and throughput of a platform. This lack of universal reference standards negatively impacts the growth potential of multiplex affinity-based technologies from a research tool to a robust and reliable clinical tool.

Stage of Innovation Where Barrier Appears: R&D

Measurement-Problem Part of Technical Barrier: No standardized reagents exist for testing the performance of protein chips.

Potential Solutions to Measurement Problem: Solutions include the development of well-characterized physical proficiency testing standards that cover a relevant dynamic range. The biological material should be a complex component (one that contains many proteins or peptides) that resembles a relevant physiological material. The component should also cover a broad range of molecular masses. Concomitantly, the development of complimentary antibodies (affinity agent) should be developed for the scientific community. In addition to physical reference standards, universal definitions of type 1 error and what variables need to be addressed when making intra- and inter-laboratory comparisons need to be defined.

NIST National Measurement System Assessment

Case Study – Measurement Needs

Technology at Issue: Proteomic-based Biomarker Discovery - Data Analysis Tools and Databases

Submitters: Members of Executive Committee - USMS Measurement Challenges in Proteomics Workshop, 3/12/2006, Boston, MA

Technological Innovation at Stake: Proteomics research generates substantial amounts of data, too much to be analyzed directly by an individual researcher or a research team. Software data analysis tools are required, to compile research results, to compare data to data in compiled databases, and to interrogate the experimental data against protein sequence databases for protein identification. Unfortunately, because there is a lack of standardized and validated data analysis tools, the identification of proteins in common samples widely depends on the data analysis tools used. This variability casts doubt on the results of proteomic biomarker discovery, ultimately limiting the success of proteomics to produce breakthroughs in clinical diagnostics, drug discovery, and fundamental biochemical and biomedical research.

Economic Significance of Innovation: If the current problems in proteomics, of widespread irreproducibility and lack of scientific validation of proteomic research results, continue to grow, it is likely that the confidence in the results of proteomics research will diminish. This will adversely impact the future growth of this scientific discipline, economically and scientifically and may stifle opportunities that proteomics will produce breakthroughs in medicine and clinical diagnostics. The economic impact will be enormous, not just in terms of the reduction of research supplies and instrumentation for proteomics, but in the economics and social benefits that might be lost from potential medical therapeutic and diagnostic breakthroughs.[are there any positive benefits to be cited? The tone here is pretty negative.]

Technical Barrier to the Innovation: Advanced data analysis tools have been developed for proteomics but there has been little absolute validation of their output or the establishment of comparability between different data analysis tools. Widely accepted standardized proteomic data sets and databases of proteomic tandem mass spectra do not exist. The barrier to the successful use of proteomic data analysis technology to aid in the discovery of new clinical biomarkers is the lack of data sets and databases to standardize and validate proteomic data analysis tools.
Stage of Innovation Where Barrier Appears: R&D

Measurement-Problem Part of Technical Barrier: Without a rigorous evaluation of the data analysis tools used in proteomics, it is impossible to access individual and inter-lab reproducibility of measurements. This is a key element in the determination of the rates of true positives and false negatives reported in qualitative proteomics investigations.

Potential Solutions to Measurement Problem: Evaluated, standardized proteomic data sets are needed to validate the performance of existing data mining algorithms and other interpretive tools for proteomics data. Data sets would consist of tandem mass spectrometric data from known peptides from well-characterized proteins. The quantity and quality of data within the dataset should closely match that of the data obtained in typical proteomics research data. Additionally, freely accessible libraries of experimentally derived tandem mass spectra of peptides would assist in the development of more advanced data analysis tools.