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Impact of measurement and standards infrastucture on the national economy and international trade

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Abstract

The U.S. federal government has a strong role in metrology R&D in the U.S. because of its importance to the nation's economy and the Constitutional authority given to the National Institute of Standards and Technology (NIST). However, pressures to maintain a balanced budget require careful planning and priority setting to win support for metrology R&D programs. The payoffs of good planning and resource deployment come in the form of anecdotal examples of significant industrial outcomes and comprehensive evidence of impacts through formalized studies. Furthermore, when tariff-based barriers to international trade are lowered, consistent and accurate measurements that are globally accepted facilitate the elimination of any remaining technical barriers to trade. We will explore these issues, giving specific examples of impacts from recent work at the National Institute of Standards and Technology.

Keywords: Metrology; Impact; Trade

1. Introduction

From its very inception, the United States government established the Constitutional authority of Congress to "... *fix the standard of weights and measures* ..." (Constitution of the United States, Article 1, §8). The national importance of metrology and measurement standards in the U.S. was again recognized in the early 20th century and a commitment to a strong federal role was legislated in 1901, forming the National Bureau of Standards (NBS) and charging it with the responsibility for:

> "... *the custody of the standards*; *the comparison of the standards used in scientific investigations, engineering, manufacturing, commerce, and educational institutions with standards adopted or recognized by the Government*; ... *the testing and calibration of standard measuring apparatus*; *the solution of problems which arise in connection with standards*; *the determination of physical constants and the properties of materials*; ... *That the bureau shall exercise its functions for the Government of the United States*; *for any State or municipal government within the United States*; *or for any scientific society, educational institution, the firm, corporation, or individual within the United States engaged in manufacturing or other pursuits requiring the use of standards or standard measuring instruments*."

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This well-defined role for NBS was re-articulated and expanded when the Bureau was renamed the National Institute of Standards and Technology (NIST) in the Omnibus Trade and Competitiveness Act of 1988. NIST was called on to:

> “ . . . *augment its unique ability to enhance the competitiveness of American industry while maintaining its traditional function as lead national laboratory for providing the measurement, calibrations, and quality assurance techniques which underpin U.S. commerce, technological progress, improved product reliability and manufacturing processes and public safety*;”

Simply stated, the NIST mission is to “*promote economic growth by working with industry to develop and apply technology, measurements, and standards*.”

The federal role in metrology is becoming ever more important as the health of domestic industries becomes more dependent on global trade. Entire industrial sectors require substantial expenditures in the infrastructure of measurement science to effectively compete in world markets. For example, a recent study found that the U.S. semiconductor industry invested more than $650 million in 1990 on metrology alone. In 1996, the investment jumped to about $2.4 billion, with a projected investment of $3.5 to $5.5 billion by 2001 [1].

Within NIST, the Measurement and Standards Program provides technical leadership for the U.S. measurement and standards infrastructure, and assures the availability of essential reference data and measurement capabilities. To effectively carry out its metrology mission, NIST competes for resources in a context of budgetary constraint that has changed dramatically over the last several years. Until relatively recently, the strength of U.S. R&D depended on the commitment of the government to maintain a stable R&D portfolio at the federal level. During the Cold War, the motivation of national security was strong enough to justify a substantial government role in research and technology development. Now this compelling driver that forged a bipartisan commitment to science and technology has disappeared.

The effect can be seen in the leveling off of federal investment in defense R&D (see Fig. 1). Initially there was a corresponding increase in non-defense R&D funding, but over the last few years our total investment is flat, even in current dollars, at approximately $70 billion for 1997 [2]. In reality only $41 billion of that is what could be referred to as science and technology base. The rest ($29 billion) is invested in short-term projects unique to specific defense weapons systems, with limited usefulness to the general economy. Of the $41 billion, nearly one-third is spent on health related research.

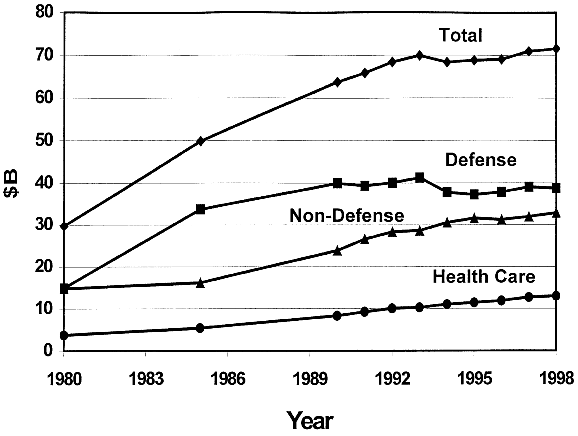

Fig. 1. U.S. federal R&D funding trends (current $) [2].

Thus the U.S. federal investment in every other field of science and technology, from physics and materials to computing and communications, from energy and environment to software and simulation, is only $28 billion out of the total federal budget of about $1.7 trillion. The U.S. government’s decision to balance the budget also makes it increasingly difficult for the R&D enterprise to continue to claim the level of public resources to which it has become accustomed.

At the same time, while the U.S. explores ways to reduce technology investments, Japan is increasing its R&D investments (Fig. 2). Japanese total public and private R&D spending as a percent of GDP already exceeds that of the U.S. In non-defense R&D, Japan’s relative investment is larger than that of the United States. We also note with interest the Japanese Science and Technology Plan of 1996, which urged the government to double its science and technology budget within 5 years, spending $155

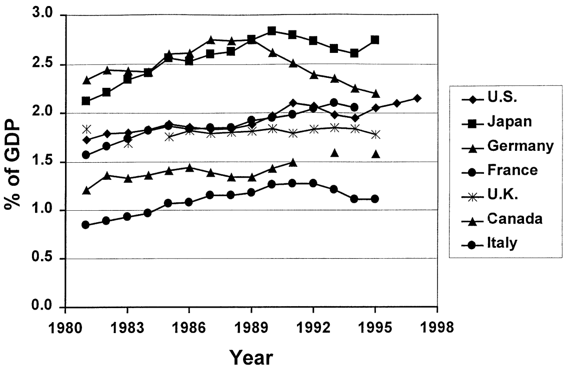

Fig. 2. International R&D spending trends [2].

billion between 1996 and 2000, of which 95% would be targeted at civilian technologies [3].

Notwithstanding the shrinking federal R&D outlay and the expanding foreign investments, U.S. manufacturing industry investment in constant 1987 dollars has been largely unchanged. The recent upward trend in total industry investment is entirely due to a reformulation of the statistics to include the increasing amounts of R&D from the nonmanufacturing industries sector (see Fig. 3). Compounding these pressures on R&D, we are seeing a significant change in the mix of R&D activity in U.S. industry, away from longer-term exploratory research and toward shorter-term business goals. Today, business units drive the work of industrial R&D organizations and this work is predominantly focused on shorter-term product development and process improvement. Many large companies have either eliminated or significantly reduced their central R&D laboratories. Increasingly they are turning to university researchers for new technologies.

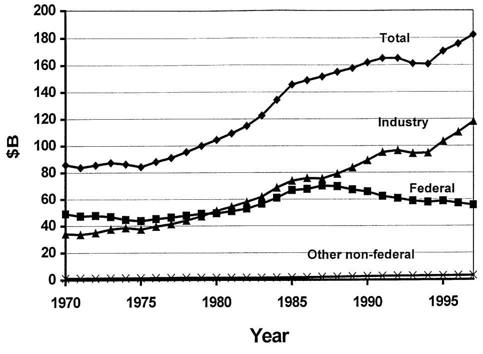

Fig. 3. U.S. R&D expenditures (constant $) [2].

The pursuit of better measurements and the delivery of measurement services feel the same stresses and strains of the post-war paradigm that affect all forms of R&D. With fewer dollars available, we have to ensure that our investments really count, especially in the eyes of our customers and decision makers. But linking the payoffs of better metrology can be quite difficult because of the infrastructural nature of measurement science. Incremental improvements in metrology can have significant impact, but only if viewed over time. Research in measurement science should anticipate practical needs so that metrological capabilities are ready when industry requires them. In such cases, it can be a challenge to describe the projected impact of present programs based on future needs. The time frames can be long and the relationships between specific metrology developments and realized benefits can be indirect. No one can deny, however, that metrology is especially important in a high-technology based economy. The challenge is to leverage the available resources to gain the best output through a process of setting priorities and designing technical strategies.

NIST laboratories serve a growing list of needs from established customer industries, and must simultaneously work to assure the technical infrastructure for the industries of tomorrow. NIST laboratories set their work priorities in accordance with criteria that take into account industries' needs, NIST's mission, and the laboratories' capabilities [4].

NIST identifies industry's leading metrology needs and generates agreement on technical objectives by using conferences, workshops, direct technical exchange with industry, technology roadmapping exercises, and joint research through participation in consortia and Cooperative Research and Development Agreements (CRADAs). In addition, NIST uses technology assessments and economic impact analyses in its strategic planning process. Through all these channels, industry input helps to set the direction and emphasis of NIST programs, and encourages individual companies to shape and participate in new initiatives. NIST also strives to anticipate metrology needs generated by new regulations by monitoring legislative developments and consulting with regulatory agencies.

2. Impact on the national economy

It is now well accepted that technology R&D is critical to an advanced nation's long-term economic growth [5]. However, neither the federal government nor the private sector has reached a consensus on the best methods for measuring the results of investments in new technology. Returns on metrology R&D typically do not begin to accrue until several years after the research is completed. Furthermore, the diffusion of such benefits impacts broad sectors of the economy, making the assessment of economic impact a complex and long-term endeavor. Economic effects can be projected but never known with certainty in advance.

The Government Performance and Results Act (GPRA) enacted in 1993 requires all agencies of the U.S. federal government to measure and report annually on the results of their activities. Agencies are required to develop strategic plans that set goals for a 5-year period and translate these goals into annual measurable targets. Setting goals and measuring the results of research present substantial challenges. The Committee on Science, Engineering and Public Policy (COSEPUP) of the National Academy of Sciences has addressed the issue of measuring and evaluating research in compliance with the requirements of GPRA [6]. COSEPUP examined bibliometric analysis (counting publications and citations), estimating the rate of economic return (impact studies), peer review, case studies, retrospective analysis, and benchmarking as tools for measuring the results of research. For fundamental research, COSEPUP singled out peer review as the best approach, because of the long-term nature of payoffs for this activity. However, rates of return, case studies, and benchmarking were also recognized as important elements, especially for measuring the impact of applied research. NIST employs a balance of all the recommended elements of the COSEPUP study. In this report, we would like to highlight our efforts to use case studies and formal economic studies as tools to measure the impact our programs have on science, the economy, and social well-being of the U.S.

The NIST laboratories select priorities carefully, matching them to the NIST mission to promote equity in trade, public health and safety, and environmental quality, by providing technical leadership for the Nation's measurement and standards infrastructure, and assuring the availability of essential reference data and measurement capabilities. NIST uses information from short, intermediate, and long-term performance measures to help decide where and how to invest its resources. NIST programs have long been guided by measurement and evaluation systems as NIST sets priorities, evaluates operational performance, and assesses near- and long-term returns on its investments and activities. Although it is not always easy to assess the impact of metrology R&D, both anecdotal information and more formal impact studies comprise the documented evidence. Examples of some informal case studies from the Chemical Science and Technology Laboratory as well as results of formal NIST impact studies are described in the following sections.

2.1. Informal case studies

2.1.1. Cholesterol measurements

Chemical metrology is at the heart of accurate medical diagnosis and the development of measures to improve our health and ensure long life. In the U.S. about one trillion dollars are spent each year on health care, which is over 13% of our GDP. More than 20% of these expenditures are for measurements. It is estimated that over 29% of these measurements are performed for control samples, quality assurance checks, and tests to confirm abnormal results [7]. Clearly, improvements in the reliability of chemical measurements in this area would have a significant economic impact for our country.

In the area of cholesterol measurements alone, it has been estimated that measurement uncertainty was on the order of ±18% relative in 1969, before any reference materials were available [8]. Over the last three decades, NIST, in cooperation with the College of American Pathologists (CAP), has developed a series of highly accurate and precise methods for a number of clinically important serum constituents, including cholesterol. These methods are recognized by the international clinical laboratory community as ‘‘definitive’’ and have been used to certify a series of cholesterol Standard Reference Materials (SRMs). The first pure crystalline cholesterol (SRM 911) was introduced in 1967. Using the definitive method, serum cholesterol SRMs were developed in 1981 (SRM 909) and again in 1988 (SRMs 1951 and 1952). These SRMs have led to a steady decrease in the number of false positives and negatives resulting from clinical laboratory results for cholesterol in blood to between ±5.5% to 7.2%, relative (see Fig. 4). Based on the number of cholesterol tests per year [9] and the average rate of re-tests, this four-fold improvement represents potential savings of almost $100 million per year in treatment costs for misdiagnosed patients, in addition to the lives saved through timely and accurate diagnosis.

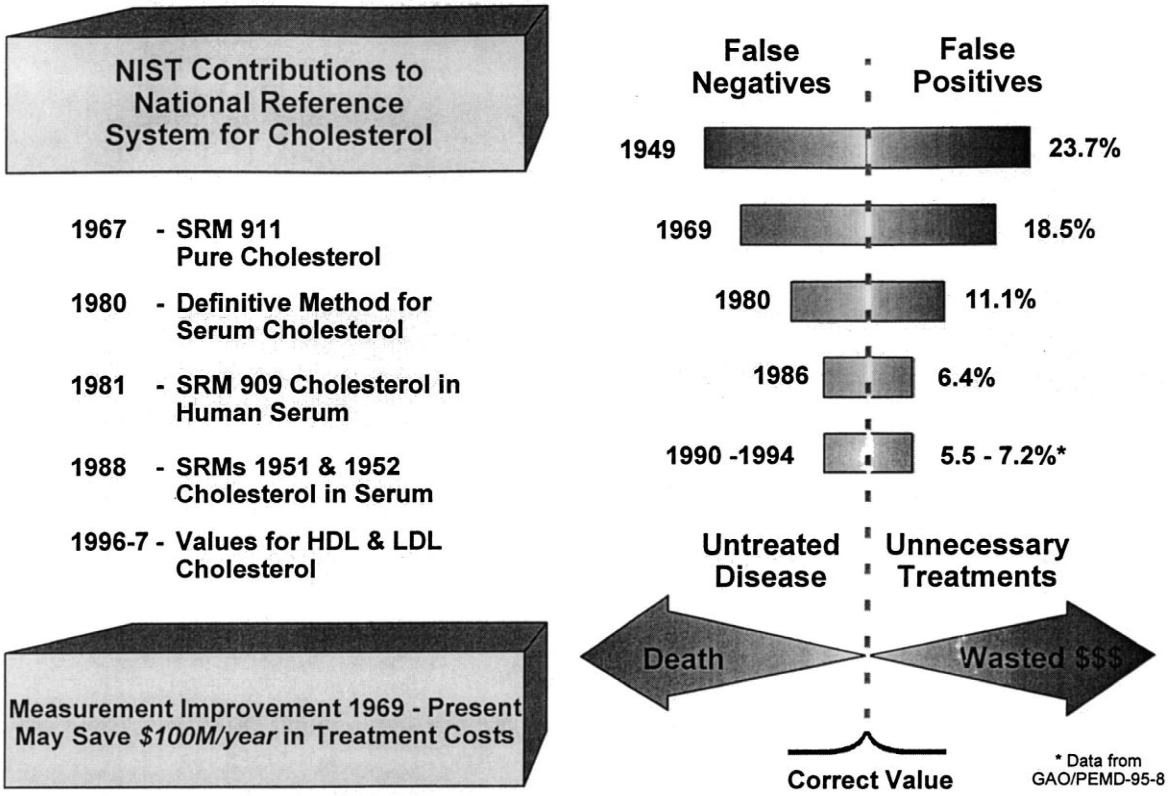

Fig. 4. NIST R&D on cholesterol measurements.

2.1.2. Natural gas

NIST has completed a series of projects that have significantly reduced the uncertainty of orifice meter measurements in the metering and sale of natural gas. The NIST work directly impacts the metering of all natural gas pipeline operations in the U.S. (about $60 billion per year), the processing of natural gas into products such as propane and butane, and the sale and use of supercritical carbon dioxide from natural gas fields. The industry segments benefiting from the research include gas producers, national and local distributors, processors, and the millions of customers of natural gas in the nation.

NIST flow measurements have resulted in a database of orifice discharge coefficients developed in cooperation with the American Petroleum Institute, correcting a long-standing error of about 0.25% in the value of orifice discharge coefficient over their range of use [10]. Based on the value of U.S. annual natural gas consumption, the impact of resolving this error in gas metering is estimated to translate into annual savings of about $200 million in the natural gas industry. Specific examples of the significance of other accomplishments are:

- NIST, under the sponsorship of other government agencies, numerous industrial companies, and the Gas Research Institute (GRI), has investigated the effect of ‘‘non-ideal’’ conditions on the performance of flowmeters in industrial installations. NIST results on installation effects have been integrated into industry standards thereby reducing the daily cost of $0.14 million in the U.S. for each increment of only 0.1% relative measurement bias.
- NIST, in collaboration with the GRI, the Gas Producers Association and the Department of Energy, has provided Standard Reference Data for the constituents of natural gas and developed the capability to predict the properties and heating values for a wide variety of natural gas and hydrocarbon mixtures. In addition, NIST has developed models for the properties of pipeline carbon dioxide, propane, and related natural gas products. These models, used to calculate the sale value of those gas products, are an order of magnitude more accurate than models previously used by industry.

2.1.3. NIST traceable reference materials (NTRMs)

In order to respond to the requirements of the 1990 Clean Air Act, regulators, specialty gas producers, and end-users of gas standards generated such a demand for gas SRMs that over 15% of NIST SRM production resources were devoted to this area each year. NIST worked with ten commercial specialty gas vendors to develop a protocol for the production and value-assignment of NIST traceable gas mixtures used to implement the ‘‘emissions trading’’ provisions of the Act. The protocol specifies that vendors manufacture a batch of cylinders and measure them against a NIST gas standard. They send both the data and one cylinder from the batch to NIST. NIST measures the batch standard against a NIST primary standard and uses the vendor data to provide both quality assurance and value assignment to each cylinder in the batch. Vendors can then use the certified batch to prepare and analyze similar mixtures for sale to end-users. Compared to an average output of 300 SRM cylinders per year, the NTRM program leverages fewer than 100 batch measurements per year at NIST into a total of over 4200 cylinders traceable to NIST. In turn, these NTRMs have been used to produce about 300 000 commercial gas standards, traceable to NIST at a value of over $75 million. In addition, the timeliness of NIST response has been significantly improved to about three months, compared to an average of 2 years or more that are required to produce a new gas SRM.

2.1.4. Reference materials for the automotive industry

Another consequence of the Clean Air Act is the development of new gasoline formulations to reduce the emissions from automobile exhausts. federal law mandates the sale of reformulated gasoline in nine U.S. metropolitan areas with the worst ozone smog: Baltimore, Chicago, Hartford, Houston, Los Angeles, Milwaukee, New York, Philadelphia, and San Diego. Some other cities voluntarily require reformulated gasoline. About 100 billion liters of oxygenated and reformulated gasoline are produced in the United States each year at an added cost of $825 million over that of regular gasoline. EPA claims that its use has the same effect on the environment as taking 7 million cars off the road. NIST has certified 12 gasoline SRMs for various oxygenates and formulations. Reducing the uncertainties of oxygenate determinations from ±15% relative, typical of the performance of standard methods, to the SRM uncertainties of a few percent represents an annual savings of over $150 million based on the material cost of one oxygenate, MTBE alone [11].

NIST has also developed specialized measurement methods and produced SRMs for use in determining the precious metal content of automobile catalysts. The availability of SRM 3144 (Rhodium Spectrometric Solution) enabled long-standing disagreements among commercial rhodium standards of up to ±7% relative to be resolved. Currently the annual value of rhodium demand is nearly $300 million dollars [12,13]. The discrepancies represented over

$21 million, but the NIST calibration material has reduced that by a factor of 20.

NIST also developed and transferred to the automotive catalyst industry a high-accuracy method to determine platinum-group elements in new and spent catalyst material. Two used-catalyst SRMs were certified for platinum, palladium, rhodium, and lead to uncertainties of less than 1% relative. Results from previously used methods often disagreed or had relative uncertainties of a few to several percent.

2.1.5. Inert gas atomization of metal powders

A NIST/industry consortium developed automated processing technology for producing rapidly solidified metal (RSM) powders. These powders are used to make special high-performance materials for jet engines and advanced magnets. Instead of casting these parts by pouring molten material into molds, or first forming billets that have to be machined, the RSM process converts the molten material into a fine powder using inert gas atomization. The powder can then be loaded into molds and, if it is fine and uniform enough, hot isostatic pressing with very little final machining is all that is needed to produce the parts. After 6 years of work the process was perfected resulting in increased efficiencies and lower costs for this production method. One crucial part of the work was a computer model developed at NIST. This model enabled engineers to simulate accurately the production process defining the relationships between processing parameters and powder characteristics. Model development and validation was possible through in-process sensors and real-time measurements of particle size distribution. One of the consortium member companies was able to re-design its gas delivery system based on the NIST model thereby increasing its output of usable atomized powder by over 40%. At the same time, the new system consumed less argon gas, helping to reduce operating costs.

2.1.6. Sulfur in fossil fuels

The sulfur content of fossil fuels is one of the most important intrinsic factors that determine their price. The accurate determination of the sulfur concentration in fossil fuels is required as a result of environmental regulation that places increasingly lower limits on their sulfur content and the imposition of large fines for non-compliance. At every stage in the process (mining, transportation, buying and selling, and combustion) the sulfur content of both oil and coal must be determined in order to meet buyer and seller specifications that are dictated in large part by government environmental regulations. The efficient and cost effective movement of coal and oil from the mine and well to power plants and refineries requires precise and accurate determination of sulfur content in two or more laboratories. For equity in trade and the efficient production of energy, it is mandatory that instrumentation in these laboratories be calibrated using accurate standards.

NIST has developed a primary method based on isotope dilution mass spectrometry (IDMS) to determine sulfur in fossil fuels to an accuracy of better than ±0.1% relative. Using the IDMS method, NIST has certified the sulfur content in a number of coal and fuel oil SRMs. These SRMs provide industry with the primary calibration materials needed for instrumentation used in routine measurements. SRMs also provide industry with a strong traceability link to NIST for such measurements, whether they be for setting the price of fuel or for demonstrating compliance with environmental regulations.

Since 1993, the sulfur content in on-road diesel fuel could not exceed 0.05% by mass. This sharply lower standard for the sulfur content of on-road diesel fuel affects 46% of the total domestic demand for distillate fuel oil, 8% of total U.S. demand for petroleum products or 23.6 billion gallons of diesel fuel. The higher operating and capital costs required to produce low-sulfur diesel fuel yields a price premium of 3–4 cents per gallon over the price of heating oil and other higher-sulfur distillates. A 4-cents-per-gallon increase in diesel fuel price is an increase of almost 1 billion dollars annually.

In 1999, electric power generation from coal alone is expected to produce 10 million tons of sulfur dioxide emissions in the U.S. [14]. The current trading price for regulated sulfur dioxide emissions credits is $150 per ton. This represents $1.5 trillion in sulfur dioxide.

The market indicators and the apparent high degree of leverage for NIST effort and industrial impact have led CSTL to begin the process to conduct a formal impact study in this area.

2.1.7. Standards for DNA testing

In some cases, NIST output does not directly impact industry, but results improve efficiency, reduce cost, and promote the widespread use of accurate measurements in other sectors. The Department of Justice's ability to implement DNA testing has benefited greatly from NIST reference materials and measurements. In the United States, DNA testing provided the first criminal conviction based on DNA in the 1986 case of *Florida v. Andrews* [15]. As of January 1, 1990, DNA tests had been admitted into evidence in at least 185 cases in over 35 states. By the late 1990s the FBI was performing over 600 000 DNA evidence examinations per year [16].

Because the results of DNA testing can be so powerfully convincing, and they often are the main reason for convictions, it is important to ensure that such tests are done correctly. DNA testing in general seems to have been accepted by courts as reliable evidence, but there have been specific cases where the tests were not done correctly and the results were not admitted as evidence.

To further address quality assurance issues of DNA testing, the 1994 Omnibus Crime Bill established the FBI's DNA Advisory Board. The Bill specified that the board must have a member from the NIST Technical Staff. DNA Quality Assurance recommendations by the DNA Advisory Board were signed by the FBI director in July 1998. These require laboratories to check their DNA procedures annually, or whenever substantial changes are made to the protocol(s), against an appropriate and available NIST Standard Reference Material (SRM) or a reference material traceable to NIST. As of October 1998, all laboratories that receive federal funding for DNA testing are required to follow the DNA Quality Assurance Standards.

The first NIST DNA Profiling Standard (SRM 2390) was completed and released in 1992 to address the principle areas of need for measurement standards in DNA testing. Shortly after introduction of this SRM, Collaborative Testing Services, Cellmark Diagnostics, and the CAP established commercial proficiency testing programs. This SRM greatly improved the reliability of forensic DNA testing. The SRM was recognized as one of that year's top 100 technological advances with a prestigious R&D 100 Award in 1993.

NIST SRM 2390 and SRM 2391, based on the newer polymerase chain reaction (PCR) technology, have significantly reduced forensic testing costs, while improving accuracy, and providing legally defensible traceability for this measurement system nationwide. A study is currently underway to develop an authoritative economic impact evaluation of DNA SRMs by private sector laboratories engaged in DNA testing. It is anticipated that significant economic benefit will be derived from the increased accuracy of analyses and the increased acceptance of DNA data in legal proceedings.

2.2. Formal impact studies

Another more formal way to measure the results of NIST metrology R&D is through an ongoing program of economic impact studies. Evaluations of the economic impact of NIST's R&D in specific technical areas are carried out through NIST-commissioned studies, mostly performed by external contractors. These studies provide both qualitative assessments and quantitative estimates of the economic impacts resulting from the several categories of technology infrastructure that NIST provides to U.S. industry. Quantitative estimates are provided either as benefit–cost ratios or as rates of return to the nation (social rate of return). Practically, only a few of these in-depth analyses are possible each year. Some of the results of these formalized impact studies are plotted in Fig. 5. By their nature, these studies are retrospective and, because considerable time is required to allow impacts to appear and be measured, the actual impact data and analyses are usually only available a number of years after project initiation. However, over time, the results of studies conducted to date have consistently shown high rates of return from NIST research, relative to both private investments in technology and other public technology investments. These results are not surprising, given that NIST targets its research at specific infrastructure problems that are typically faced by a large number of firms and/or industries, and which have been identified through cooperative strategic planning with industry. The results of these impact assessments not only respond to the need to measure and analyze current and past performance but also contribute to future strategic planning [17].

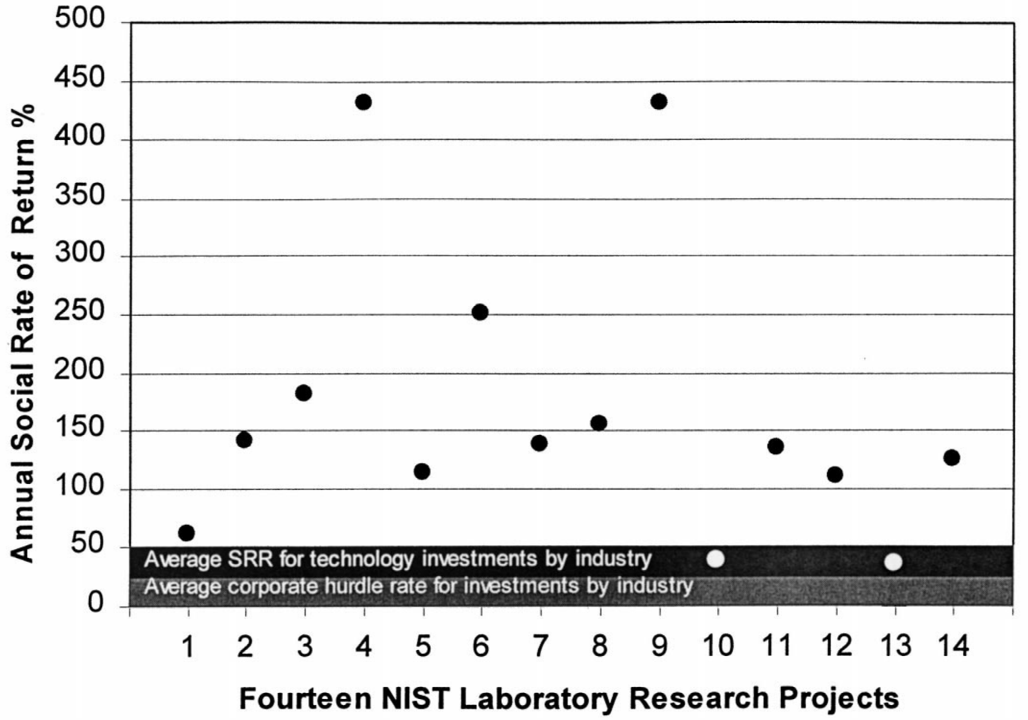

Fig. 5. NIST R&D rate of return compared to industry.

2.2.1. *Radiopharmaceuticals*

In response to industry-wide concerns expressed in the early 1970s, NIST (then NBS) began a program to supervise and administer on behalf of the Atomic Industrial Forum (now the Nuclear Energy Institute) a measurement quality assurance program for the radiopharmaceutical industry. NBS also entered into an interagency agreement with the Food and Drug Administration to ensure the continuous availability of national radioactivity standards for use by the radiopharmaceutical industry. In 1997 a planning report on the Economic Evaluation of Radiopharmaceutical Research at NIST was published [18]. The purpose of this report was to document and quantify selected broad-based economic impacts associated with NIST's research activities in radiopharmaceuticals.

Radiopharmaceutical Standard Reference Materials are produced by NIST for the members of the NEI/NIST Radioactivity Measurement Assurance Program (MAP) and for other end-users. In general, the 28 radiopharmaceutical standards are certified with a relative uncertainty of ±1%. Other producers of radioactivity calibration standards provide materials that are traceable to NIST using these SRMs, but the propagation of uncertainty generally leads to a relative uncertainty of ±5% for such commercial standards.

The approach selected for evaluating the economic impacts associated with NIST radiopharmaceutical research was to compare the actual NIST costs related to the production of radiopharmaceutical SRMs to estimates of the economic benefits received by SRM users. Economic benefits were estimated through surveys and interviews designed to elicit approximate additional costs that would be incurred by radiopharmaceutical manufacturers and patients in the absence of NIST research and delivery of the SRMs.

It was concluded that without NIST's research and SRM development, it would take between 5 and 10 years for some industry group or association to form and become accepted as a de-facto standard setting body. The total expected transaction costs during this transition period would be at least $1.3 million per year, with expected costs to rise 4% to 10% per year until a steady state situation was reached. During this 5- to 10-year transition period, the level of accuracy at the manufacturing stage would degrade from the current ±3% to between ±5% and ±10% owing to the lack of accurate reference materials and measurement methods. At the hospital, the accuracy of dosages would degrade from the current ±10% to ±15% or worse.

NIST costs and industry benefits data are presented in Table 1. The cost data for 1998 through 2001 are based on a 5.5% annual increase over the 1997 amount, which was the actual rate of increase from 1996 to 1997. The 5-year forecast period represents the conservative end of the 5- to 10-year catch-up period estimated by the participants. Manufacturers' estimates of the total industry cost savings assume a 4% growth rate in costs in the out-year estimates. The estimated cost savings to patients include avoiding re-treatment and repeat diagnostic procedures.

Typical of many cost/benefit analyses of metrology outputs, the onset of benefits is significantly delayed compared to the time period initial costs of the R&D are incurred. In this case, development of accurate measurement methods as well as the development of suitable materials for candidate SRMs took several years. Once the initial materials were available and elements of the MAP were in place, the benefits began to be realized.

Table 1
Costs and economic benefits for NIST radiopharmaceutical R&D ($k)

Year	NIST costs	Manufacturer benefits	Patient benefits	Total net benefits
1990	$210	–	–	−$210
1991	$218	–	–	−$218
1992	$218	–	–	−$218
1993	$265	–	–	−$265
1994	$226	–	–	−$226
1995	$384	–	–	−$384
1996	$364	–	–	−$364
1997	$384	$1300	$90 000	$90 916
1998	$405	$1352	$94 500	$95 447
1999	$427	$1406	$99 225	$100 204
2000	$450	$1462	$104 186	$105 198
2001	$475	$1521	$109 395	$110 441

2.2.2. Thermocouples

The NIST thermometry program includes both calibration services for and research on thermocouples. Thermocouples are among the most commonly used sensors for monitoring and control of manufacturing processes. The annual sales of thermocouple products sold by the U.S. thermocouple industry (suppliers of wire and thermocouple assemblies) into the U.S. market are approximately $280 million. The incorporation of these devices into higher levels of product structures across a broad base of domestic industries affects a much larger portion of the manufacturing sector, estimated to be on the order of $81 billion.

The thermocouple industry consists of wire suppliers and thermocouple suppliers. The customers of the wire suppliers consist of both thermocouple suppliers and thermocouple users that fabricate and assemble the devices. The wire suppliers typically perform sample measurements on each production lot of wire. Depending on the calibration accuracy requirements of a given application, these sample measurements may or may not be sufficient for users of the thermocouple. Therefore, the supplier or user/producer may perform additional measurements as necessary. Thermocouple suppliers purchase wire from the wire suppliers to fabricate and assemble finished thermocouple products. Thermocouple users cover such broad and diverse industrial sectors that it was difficult to define a reasonable sample of such a group to survey for the impact study.

The NIST Thermocouple Calibration Program (TCP) includes R&D for realizing, maintaining, improving and disseminating the national standards of temperature. The program provides users and suppliers with three main types of benefits:

- Efficiency in developing the infrastructure technology necessary for calibrating thermocouples. Industry has relied on NIST as the single organization for reference functions and tables, calibration services, and other technical support and advice. This reliance has obviated the need for duplicative research by individual companies and industrial consortia.
- Cost and time savings in resolving disputes between users and suppliers involved in thermocouple commerce. These efficiencies are based

on industrial agreements for the technical bases of standards established through NIST. These agreements are due mainly to industry's recognition of NIST's high quality outputs and impartial competitive posture.

- Improved competitiveness for domestic thermocouple users in the forms of better marketability (e.g., compatibility with international product standards), production efficiencies (e.g., process yields), and product features (e.g., performance and reliability). These competitiveness benefits are based on the high degree of calibration accuracy attainable via standards traceable to NIST.

NIST's expenditures in the TCP from 1990 to 1993 included support for research on the basic physical properties that underlie the measurement science to incorporate the change from IPTS-68 to ITS-90. For this effort, NIST led the development of the ITS-90 update, and shouldered 60% of the costs with eight other national standards laboratories. Costs over the whole period of the study (1990–1996) also include support for R&D on test methods as well as the calibration services themselves.

Benefits were estimated based on surveys and interviews of the thermocouple industry. Participants were asked to estimate the additional expenses that would have been incurred if NIST were to cease to provide primary calibration services [19].

The cost–benefit data are presented in Table 2. Once again, we note the significant time during which NIST expenditures on the fundamental and infrastructural aspects of thermocouple principles, measurement, and test methods did not result in immediate benefits to industry. But once benefits are realized, they are substantial, and these estimates do not include the much larger, though diffuse, community of device users. This study conservatively estimated the cost–benefit ratio to be 2.95.

Table 2
NIST TCP costs and net industry benefits ($K)

Year	NIST costs	Net industry benefits
1990	$220.4	–
1991	325.9	–
1992	483.2	–
1993	266.6	–
1994	206.1	–
1995	211.8	–
1996	174.7	–
1997	185.2	$2296.8
1998	196.3	2411.6
1999	208.1	2532.2
2000	220.6	2658.8
2001	233.8	2791.8

2.2.3. Alternative refrigerants

Occasionally, an accelerated R&D program must be undertaken to respond to industry needs that are constrained by set deadlines. Such was the case for NIST's program on the chemical and physical properties of alternative refrigerants used to replace chlorofluorocarbon (CFC)-based refrigerants. Until the past decade, most refrigerants used throughout the world were made up of CFCs. But as a result of research findings on the deleterious effects of CFCs on the earth's ozone layer, a global agreement to phase out the production and consumption of CFCs and replace them with alternative refrigerants was signed in 1987 (the Montreal Protocol).

NIST had been engaged in R&D to characterize, model, and predict the chemical and physical properties of chemical compounds since the early 1970s. Although many of the necessary tools for modeling and prediction were in place, NIST did not specifically focus on potential alternative refrigerant compounds until 1982, when the first discussions leading to the Protocol were initiated. A formal program in alternative CFCs was established at NIST in 1987.

With the timetable imposed by the Protocol as an incentive to develop new alternatives to CFCs, NIST engaged in research that would allow industry to make the switch to alternative refrigerants in a timely and economic fashion. NIST began by identifying the basic requirements for new refrigerants according to the new rules, and then started research on determining the physical properties of such candidate alternatives.

NIST's research into alternative refrigerants has produced technical outputs in the following five areas:

- Published results of measurements and high-accuracy models for the thermodynamic and transport properties of pure alternative refrigerants and refrigerant mixtures.

- An extensive update of the tables and charts in the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Handbook of Fundamentals.
- Participation and leadership of international efforts to develop standards for refrigerant properties (e.g., the United Nations Environment Programme, International Energy Agency Annex 18).
- A comprehensive analytical database for alternative refrigerants published by CRC Press.
- An electronic database (REFPROP) that calculates the properties of 41 pure refrigerants and mixtures with as many as five components. REFPROP has become the de facto standard for the refrigeration industry. ARI (the Air-Conditioning and Refrigeration Institute) and the Electric Power Research Institute adopted it as the primary source of properties data for its Alternative Refrigerants Evaluation Program. The NIST Standard Reference Data Program has sold over 500 copies of REFPROP since the first version came out in January 1990.

The industry concerned with CFC alternatives comprises refrigerant manufacturers as well as heating, ventilating, and air conditioning (HVAC) equipment manufacturers in whose machines the alternative refrigerants are used. There were five major CFC producers and six users of CFCs who had purchased REFPROP that were included in the impact study [20]. As is usually the case, the participants were asked to estimate the additional costs that industry would have incurred in meeting the Protocol phase-out schedule without the tools and data provided by NIST R&D.

Responses from the CFC producers indicated that they would have hired additional personnel to work on the materials characterization and analysis needed by their proprietary alternative CFCs. The smaller companies would have tried to rely on others' research in the public domain or generated as part of a consortium effort.

The users of CFCs (and REFPROP) were asked to estimate the level of additional expenditures that would have been required to ensure comparable equipment performance and reliability without the outputs of the NIST program. Responses from this group generally indicated that additional quality control engineering personnel would have been required. One respondent indicated that a substantial one-time equipment purchase would have also been needed.

Table 3 shows total expenditures for research conducted at NIST on alternative refrigerants and on REFPROP-related information, by year, along with industry reported benefits.

The relatively short time between the beginning of the alternative CFC program at NIST and the onset of industry benefits is quite different from similar analyses of other NIST R&D. This phenomenon can be traced in part to the foresight in developing the program on physical and chemical properties in the early 1970s. This program produced the generic tools

Table 3
Net industry benefits from NIST-conducted research on alternative refrigerants ($K)

Year	Total expenditures on research conducted at NIST	Total benefits reported by industry	Net industry benefits
1987	$68.0	$0.0	($68.0)
1988	75.0	0.0	(75.0)
1989	345.0	2090.2	1745.2
1990	490.0	3467.6	2977.6
1991	455.0	1658.0	1203.0
1992	830.0	1071.4	241.4
1993	960.0	1071.6	111.6
1994		1073.0	1073.0
1995		1075.5	1075.5
1996		1078.9	1078.9

needed to characterize, model, and predict the properties of broad classes of compounds, so that NIST was ready when the CFC problem arose. In addition, the CFC phase-out schedule called for by the Montreal Protocol inspired a high degree of focus on the candidate compounds that led to early useful results.

The impact study also found that there were undoubtedly other substantial benefits that could be ascribed to the NIST program. For example, in the absence of reliable data concerning the properties of alternative refrigerant compounds, firms designing refrigeration equipment would be forced to rely on less comprehensive, less accurate, and more heterogeneous properties data furnished by individual chemical producers. The costs of evaluating that data could be significant, especially for new refrigerants, and would conceivably be incurred repeatedly by numerous equipment designers, who doubted the performance claims of suppliers. Secondly, without NIST R&D the phase-out schedule agreed to might have resulted in CFC alternatives being introduced that were not optimally designed for existing refrigeration equipment. Energy efficiency of such equipment would then have been degraded leading to substantial expense compared to the present energy costs.

The examples above illustrate not only the importance of metrology for benefiting specific companies and industries, but also the broad national impact that metrology has for establishing the infrastructure that supports whole national economies.

3. Impact on international trade

With world trade increasing by 15% per year, trade policies and agreements are vitally important to create a world market with a ‘‘level playing field.’’ However, these policies alone are not sufficient to ensure fair and free access to foreign markets. Increasingly, sophisticated measurements, conformity tests, normative standards, and reference materials and data are required to deal successfully in the world market. Access to markets can be hampered by incompatible standards, or by the lack of uniform and accurate weights and measures. Among other elements, global trade requires a single system of physical and chemical measurements in all markets. These measurements must be traceable to national measurement institutes, must be uniform and accurate throughout the world market, and must evolve with advancing technology. In addition, to address global scientific and environmental issues such as global climate change, we need cohesive and self-consistent measurements and data that are mutually acceptable by all nations. Finally, effective implementation of public health and safety policies requires measurements of the highest quality.

The impact of standards harmonization on exports can be seen in a recent NIST standards assistance program in Saudi Arabia. The American business community in Saudi Arabia estimates that NIST’s efforts to harmonize standards with the Kingdom have resulted in an increase in exports to Saudi Arabia of between $300 million and $500 million per year, at a cost to NIST of about $0.5 million per year. This represents a 5% to 8% increase in the over $6 billion dollars worth of goods exported to the Kingdom, a return on investment of 600:1.

If we first consider international trade, we find the rules have changed dramatically over the last several years as the world becomes smaller and new markets emerge. World trade is increasing at the rate of 15% per year. To be players in this burgeoning activity, companies have to pay heed to the principles of ISO 9000 to assure the quality of manufactured products and of ISO 14000 to certify that they are good world citizens from an environmental perspective. They are required to have quality systems in place that document their quality assurance procedures, which in many cases are required for laboratory accreditation. Worldwide acceptance of these efforts as evidence of product quality hinges on systems of conformity assessment and mutual recognition. The foundation for all of this is state-of-the-art measurement capabilities. Measurement comparability from one laboratory to another and from one country to another forms the foundation upon which rest the building blocks of mutual recognition and acceptance.

There are still challenges where technical barriers impede the flow of trade. Some foreign markets are inaccessible in part because national technical measurements and standards do not conform to the conventions of potential trading partners. The directives of some maturing regional programs pose present and future technical barriers to trade with many developing markets, and strategic partnerships are not in place to support fair and free access to those markets. The list of such trade barriers is almost endless:

- Limits on biocide trace abundances for imports and exports of textiles and agricultural products.
- Limits on heavy metals in plastics and paints, and exhaust emissions from automotive products.
- Recylability requirements for computers and other manufactured products.
- Altimeter calibration measurement traceability at airline maintenance facilities.
- Technical specifications mandated by the EU directive on electromagnetic (EM) compatibility for all products that emit EM radiation.

We are now more aware than ever of how localized activity affects the environmental quality of the whole world. Assessing the impact of fossil fuel burning, deforestation, or the continued introduction of CFCs into the atmosphere requires that chemical measurements made in different places and in some cases over long periods of time accurately reflect physical reality. How else can models be developed to accurately assess trends in the effects of greenhouse gases and the hole in the ozone layer to predict the impacts of global climate change? And having resolved to find alternatives to CFCs, chemical and physical metrology has proven to be essential for finding alternatives that are both environmentally benign and actually work.

3.1. Achieving measurement comparability

National Metrology Institutes (NMIs) have a unique and pivotal role to play in ensuring the comparability of physical and chemical measurements. As tariffs are negotiated away, technical barriers to trade become more evident. Advances in measurements and standards are key steps to overcoming such technical barriers. NMIs need to be active in advancing the state of measurement science to support the needs of their own domestic industry. They also need to interact on a global basis with other NMIs to be recognized as being among the world's leading measurements and standards institutions. These efforts facilitate the harmonization of systems of measurement and standards and eventually lead to mutual recognition of these systems among trading partners.

The vast number of countries interested in participating in such a system makes implementation of these relationships and interactions quite complicated. The only efficient way to begin is on a regional basis. Each major world trading area includes, in some cases, many different countries in all stages of economic development. The number of bilateral agreements required by any one country to have access to world markets preclude a country-by-country approach. Trade areas first need to overlay corresponding regions of metrological cooperation. Within such regions critical measurement comparability issues can be addressed by a consensus-based approach. But comparability through consensus within a region cannot be extended outside the region. Furthermore, measurements are subject to long-term drift if they are not traceable to standards recognized among all countries and regions. When comparability is based on accuracy, measurement results are time-invariant and able to be extended worldwide. NMIs have a critical role to play in this process.

Establishing and maintaining comparability through accuracy requires a hierarchical system of standards for effective leverage from the NMI level down to routine field measurements. The relationship among measurements and standards in such a metrology system is explained by the International Vocabulary of Metrology (VIM) definition of *traceability* as:

> . . . *the property of the result of a measurement or the value of a standard whereby it can be related to stated reference, usually national or international standards, through an unbroken chain of comparisons, all having stated uncertainties* [21].

What is not included in this definition is the need to establish and maintain the integrity and stability of the traceability system. This depends critically on the continuous and systematic examination of measurement comparability including the exchange of standards and the conduct of measurement comparisons.

As an example, NIST is responsible for the U.S. system of measurement. The hierarchy of units, standards, and calibrations is depicted in Fig. 6. NIST maintains the basic International System (SI) of units, such as time, mass, electric current, and the amount of substance (mole) through measurements of the physical phenomena that define these units, and maintenance of the U.S mass artifact standards. The derived units are similarly maintained. In order to transfer the accuracy base provided by the SI, NIST provides standards, calibrations, and reference materials to U.S. industry, supporting a wide range of applications, services, and products.

Traceability to the SI within the U.S. system was initially expanded to include Canada and Mexico, leveraging the efforts of all three countries to form the North American Metrology (NORAMET) organization. Now the regional metrology organizations (RMOs) of North America, Central America (CAMET), and South America (ANDIMET and SURAMET), together with those of the Caribbean (CARIMET) have agreed to cooperate in the development of the Inter-American Metrology System (SIM). Regional cooperation leads to a wider harmonization of measurements and standards, which in turn facilitates the free flow of trade (see Fig. 7).

Although regional comparability and traceability is a necessary first step, success on a global scale cannot be achieved without wider international/interregional comparability and mutual recognition of national standards. When the system is fully implemented as shown in Fig. 8, horizontal comparability among the regional NMIs, coupled with their respective vertical systems of traceability within

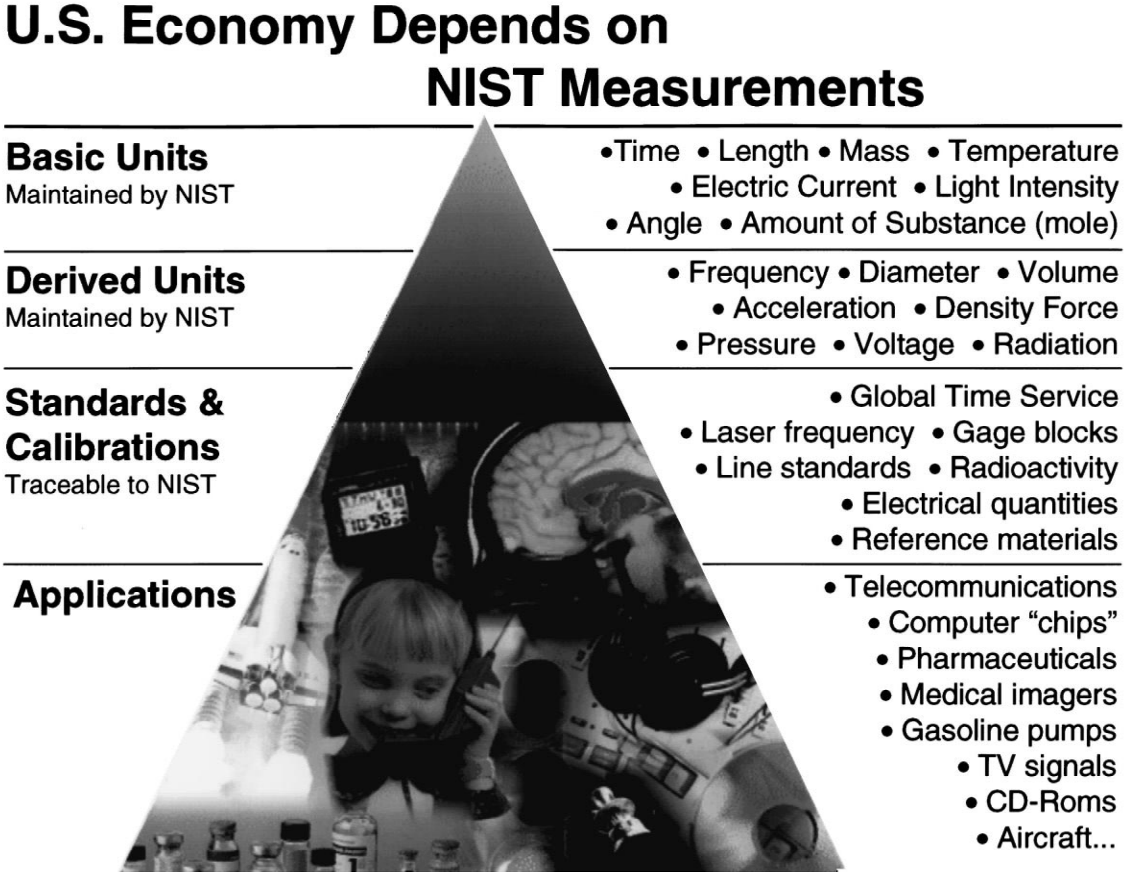

Fig. 6. U.S. traceability system and the dependence of the economy on NIST measurements.

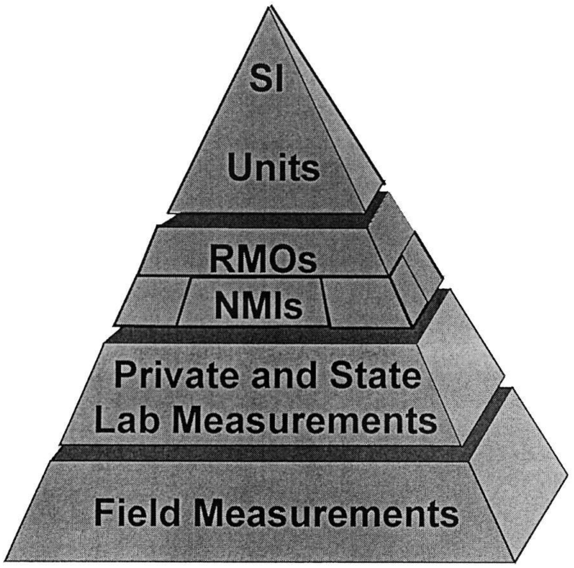

Fig. 7. Regional groups and their position in the traceability pyramid.

countries and regions, affords a multiplicity of paths to achieve measurement traceability, mutual recognition, laboratory accreditation, and product certification.

The need for continuous attention to measurement comparability and traceability is not a new concept. As early as 3000 BC, the standard unit of length, the cubit, was used to construct the pyramids. The cubit was first established as the length of the Pharaoh's forearm plus the width of his palm. The realization of the cubit, a stick of wood, became the first working standard to ensure comparability in dimensional metrology. A more durable ''Royal Cubit Master'' was struck in granite as the primary standard. Wooden cubit standards were used in the field at pyramid construction sites, and at each full moon, the one in charge of this working standard journeyed to the Royal Master to ensure the accuracy of his stick. During the time of King Cheops, the Great Pyramid of Giza was built using this system. Uniformity of length measurement was achieved to a relative accuracy of 0.05% over a distance of 230 m. Just as in ancient Egypt, periodically scheduled comparisons are an important part of today's efforts to achieve and maintain measurement comparability. For example, the data in Table 4 include the analytes, criteria, and assessment dates used to support a declaration of equivalence for gas analysis standards between NIST and the Netherlands Measurement

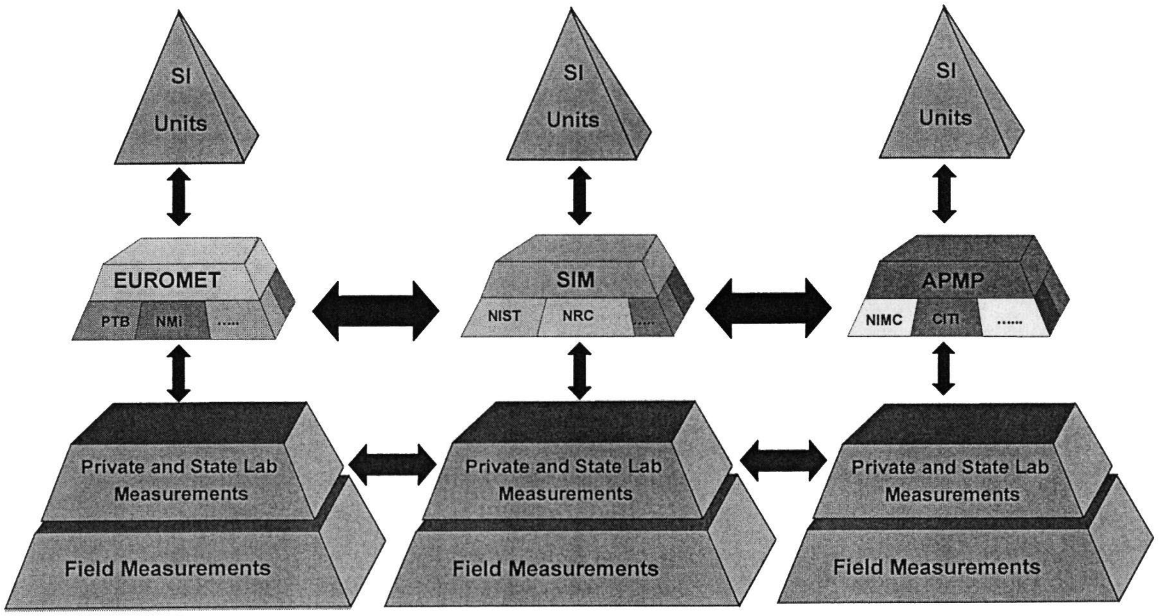

Fig. 8. Horizontal comparability and vertical traceability.

Table 4
Schedule for NIST-NMi gas standards comparability assessment

Component	Molar fractions (mol/mol)	Statistical test for Statement of equivalence	Average bias found	Date of Assessment	
				First	Second
CO_2/N_2	1×10^{-4} to 1.5×10^{-1}	Bias $<0.5\%$	0.07%	1995	1997
CO/N_2	1×10^{-4} to 6×10^{-2}	Bias $<0.5\%$	0.09%	1995	1997
Ethanol/N_2	1×10^{-4} to 2.5×10^{-4}	Bias $<1\%$	0.5%	1995	1998
NO/N_2	1×10^{-5} to 4×10^{-3}	Bias $<0.5\%$	0.2%	1995	1998
O_2/N_2	2×10^{-2} to 2.2×10^{-1}	Bias $<0.5\%$	0.05%	1995	1998
Propane/N_2	5×10^{-4} to 3×10^{-3}	Bias $<0.5\%$	0.08%	1995	1997
SO_2/N_2	1×10^{-4} to 3.5×10^{-3}	Bias $<1\%$	0.05%	1995	1998

Institute (NMi). Repeat measurements on each of the seven gas mixtures listed are conducted within a 2- to 3-year time frame to ensure the stability of the metrology that supports the declaration.

3.2. Organizing the national and regional systems

To establish a robust physical or chemical measurement system that has a significant impact on the national economy, a national system should respond to the needs of industry, government, and the scientific community. It should support regulatory requirements and be consistent with international standards. For metrology, the foundation of a national system for measurement traceability consists of a number of components. There should be in place all the resources of a measurement infrastructure including human resources and laboratory facilities and equipment. Research and measurement activities should focus on the development and practice of primary or definitive methods of measurement as well as the kinds of robust reference methods that have wider applicability and are more easily transferable to industry. NMIs need to engage on a continuing basis in regional and international interlaboratory comparisons and the exchange of scientific personnel. Additional tools such as the development and distribution of certified standards and reference materials, the establishment of quality systems and the development of a system of laboratory accreditation round out the list of essential components.

Global assurance of traceability and comparability of physical and chemical measurements requires traceability to national standards, comparability among national laboratories, and transparent equivalence of each country’s or region’s traceability structure. Once these elements are in place on a national or regional basis, a worldwide body is needed to organize the ongoing work of exchanging and comparing measurements and standards. Such an umbrella organization was first established by the Comité International des Poids et Mesures (CIPM). The NMIs are working on a mutual recognition agreement (MRA) drawn up by the CIPM that recognizes the results of measurement comparisons as the basis for accepting calibration and measurement certificates issued by the NMIs. These measurements comprise a list of (1) key comparisons of national measurement standards identified by the Consultative Committees of the CIPM and (2) key and supplementary comparisons identified by the RMOs. The key comparisons also fulfill the other essential function of international comparisons to check the estimated accuracy of independent primary realizations of the units of the SI.

4. Summary

The measurements and standards infrastructure of a nation has become an increasingly critical tool for national trade and for removing technical barriers to global trade. The resources required to maintain this infrastructure represent a significant part of the R&D investment of each country. It is, therefore, of utmost importance to articulate the impact of metrology on national economies and international trade in quantitative terms. Examples of informal case studies and formal impact studies have been presented to facilitate the expanding discussion on the importance of metrology and the significant benefits to be expected from investments in metrology R&D.

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