Planning Report 01-1

Economic Impact Assessment of the NIST's Josephson Volt Standard Program

Prepared by:
TASC, Inc.

for

National Institute of
Standards & Technology

Program Office
Strategic Planning and
Economic Analysis Group

July 2001

U.S Department of Commerce
Technology Administration

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Prepared for:

The National Institute of Standards and Technology
Program Office
Strategic Planning and Economic Analysis Group

Prepared under:
Contract No. 50SBNB7C1122
Task Order No. 5

Prepared by:

David P. Leech

Approved by:

Christopher Waychoff
Gary Payne

TASC, Inc.
1101 Wilson Boulevard
Suite 1600
Arlington, VA 22209

ACKNOWLEDGEMENTS

We wish to acknowledge the contribution of Charles G. Masi to an early version of this report. In addition, Michael Marx (TASC) made incisive recommendations for improving the analysis and presentation of the report. NIST technical staff, especially Michael Kelley and Clark Hamilton, provided extensive support in terms of patiently explaining voltage calibration processes and a complex program history. Gregory Tassey (NIST) provided critical insights that helped conceptualize the economic impacts of the program

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EXECUTIVE SUMMARY

The National Institute of Science and Technology (NIST) has been at the pinnacle of the nation's electrical measurement system since NIST's founding (as the National Bureau of Standards) in 1901. NIST maintains research and technology expertise that assures the nation's commitment to the highest international standards of measurement. NIST often leads in the development and advocacy of such measurement standards. To accomplish this mission, NIST must make investments in the development, maintenance, and diffusion of what economists call *infratechnologies*, which allow comparable measurements among industries, between industries and university research centers, and among nations.

This economic impact assessment focuses on a program that is in some ways represents a major change in standards worldwide— the shift to *intrinsic standards*. Unlike traditional *measurement standards* that rely on artifacts or experiments to produce the basis for measurement, intrinsic standards are based on constants of nature, inherent properties that are invariant and independent of the environment. Intrinsic standards hold the promise of shortening the traceability pathway from the end product back to the national laboratory. Examples of quantities supported by intrinsic standards include time and frequency, resistance, and length.

An example of this trend toward intrinsic standards is voltage measurement. When NIST was founded in 1901 the competition for voltage measurement technology was between two types of "wet cell" batteries — the Clark cell and the Weston cell. In 1905, the U.S. adopted a new representation of the standard volt based on Weston cells located at NIST. By the late 1960s, university researchers were beginning to understand the electrical properties of Josephson junctions, made of superconductor material. In cooperation with NIST (NBS), special instrumentation was built to verify the accuracy of the university's Josephson voltage standards. It was soon recognized throughout the world that a precision *intrinsic* voltage standard was possible.

In 1972, the U.S. was the first nation to adopt a representation of the volt based on the electrical properties of a Josephson junction maintained at NIST. By the mid-1980s, the national standards laboratories of most major industrialized countries used the Josephson effect to define their unit of voltage. NIST's researchers envisioned a relatively low cost and portable Josephson Volt Standard (JVS) system infratechnology to improve the way that the metrology community conducts routine calibration.

By the late 1980s, NIST began to transfer its JVS technology to sophisticated manufacturing or service production environments, such as electronic measurement instrument manufacturers and aerospace industry metrology laboratories. By the time this economic impact assessment was initiated, NIST had transferred it JVS technology to more than 40 government and private sector organizations worldwide, including more than 20 in the North America alone.

It was anticipated that the transfer of NIST's technology would result in four types of economic impacts: calibration process savings, in-service failure cost avoidance, product development savings, and profits from sales of products dependent on NIST JVS system technology. While surveys of JVS system users indicate that process and cost-avoidance savings are significant, by far the greatest measurable impact has been on enabling leading instrument manufacturers to come to market sooner than their international rivals, with the most sophisticated new measurement technology, and to profit accordingly. This is reflected in the measures of economic impact presented in the table below.

Table 1. Estimates of Economic Impact

Performance Metric	Estimate
Net Present Value in 1987	$18,700,000
Net Present Value in 2000	$45,100,000
Real Social Rate of Return	877%
Benefit-to-Cost Ratio	5

1. BACKGROUND

1.1 ECONOMIC IMPORTANCE OF ELECTRICITY

To a large extent, electricity defines modern technology-based civilization. For the entire 20th century, electrical power and the devices it supports have been a driving force for the U.S. economy. The scale of electrical production and its widespread use in the automotive, aircraft, chemical, machine tool, and, most recently, the telecommunication and computer industries has led economic historians to refer to the 20th century as "the age of electricity."[1] In just over 100 years, electricity has radically transformed and expanded our energy use.

> Electricity is clean, flexible, controllable, safe, effortless, and available instantly. In homes, it runs everything from toothbrushes and televisions to heating and cooling systems. Outdoors, electricity guides traffic, aircraft, and ships, and lights up the night. In business and industry, electricity enables virtually instantaneous global communication and powers diverse devices that include trains, auto plant assembly lines, restaurant refrigerators, and automatic pin-setting machines at the local bowling alley.[2]

The penetration of electricity into our economy and way of life is reflected in the nearly unbroken 50-year pattern of increasing electric power sales.[3] From 1949 to 1997, while the population of the United States grew by 79 percent, the total amount of electricity sold grew by more than 1,100 percent. Per-capita average consumption of electricity was almost seven times higher in 1997 than in 1949.

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[1] S. Ratner, J. Saltow, and R. Syllva, *The Evolution of the American Economy*, Basic Books, 1979.

[2] Energy in the United States: A Brief History and Current Trends, US Energy Information Administrations, http://www.eia.doe.gov/emeu/aer/eh/eh.html#TE, May 1999.

[3] Two years—1974 and 1982—are the exceptions to the long-term trend. *Energy in the United States: A Brief History and Current Trends*, U.S. Energy Information Administration, April 1999.

1.2 VOLTAGE

The measurement of electrical parameters is fundamental to the producers of electrical power as well as to the designers, producers and users of devices that employ electricity. All electrical systems are designed to produce information or do work. The services they provide and the proper functioning of their devices require accurate measurement of voltage (V), current (I), and resistance (R). Ohm's Law (V=IR) describes the relationship among them.

Also called "potential energy," "potential difference," voltage is an electrical property that is basic to the structure of matter. Voltage in an electrical system is analogous to water pressure in a faucet or a hose.[4]

Accurate measurement of voltage is extremely important in a wide range of instrumentation. Specifically, voltage measurement is an important parameter for the following four broad classes of instruments:

- Voltage measuring equipment
- Process control instruments
- Electrical integrating instruments
- Analytical and scientific instruments.[5]

1.3 CALIBRATION

Every device that used to measure electrical energy must be calibrated to assure its accuracy. Such calibration assures that the uncertainty in measurement readings is within specified limits.[6] While the influence of metrology and calibration is pervasive, the average person knows little about the infrastructure and practice of measurement generally, and less still about the infrastructure and practice of electrical measurement in particular. Thus, little public attention is paid to these important

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[4] W. E. Hafford and E. W. McWhorter, *Understanding Solid State Electronics*, Howard W. Sams & Co., 1984.

[5] These correspond with the following Standard Industrial Product Codes: 38252, 38230, 38251, and 38260.

[6] "Accuracy" is the difference between the measurement result (datum) and the actual value of the physical quantity being measured. "Precision" is the smallest difference a measuring instrument can report, and is a function of the instrument used to make the measurement. Non-metrologists usually judge the quality of a measurement in terms of accuracy. Metrologists, on the other hand, prefer to use the term "measurement uncertainty," which has the advantage of being defined rigorously.

measurement issues because they are regulated and performed behind the scenes in accordance with laws and contracts.[7]

Calibration is performed by, or in conjunction with, metrology laboratories according to daily, weekly, monthly and annual routines. The main business of a metrology laboratory is the calibration of test equipment, as well as the development and maintenance of processes for conveying accurate calibrations to all measurement and test equipment in its purview. In a general sense, calibration is a set of operations performed in accordance with specific documented procedures for comparing measurements made by one instrument to those made by a more accurate instrument or standard. The purpose of calibration is to detect and report errors in the instrument tested, and to eliminate these errors by making adjustments.

In a manufacturing or service production environment, routine tests of production processes and products involve a wide variety of test equipment that must be calibrated to assure the quality of these products and processes. The costs of the facilities, equipment, training, and operation of metrology labs are returned in:

- More reliable instruments
- Better control of manufacturing processes
- Fewer manufactured items that must be diverted for re-test or re-work
- Greater sales of products and services to customers satisfied with an organization's quality practices.

Perfect products, perfect manufacturing equipment, and perfect test equipment are not possible. What is possible, and what manufacturers seek to achieve, are characterizations of quality, most generally in terms of accuracy (uncertainty) and precision. The job of industrial metrologists, and the mission of NIST in supporting the metrology community, is to assure the best possible calibration procedures for maintaining or improving product and service quality.[8] Ultimately, the struggle for product and service quality assures the competitive position of U.S. producers in domestic and

[7] For example, we take for granted that two clocks in different locations read the same. In fact, the accuracy of our watches is often measured against a standard source by "calling time." We assume that a pound of hamburger is roughly the same regardless of where it is purchased, and while we may be aware that grocers' scales are "inspected," we take it for granted that the scale's accuracy is maintained regularly. We also assume that the temperature on a new oven is accurate, so that it will cook food in roughly the time indicated in a cookbook.

[8] Metrology is the science and practice of measurement, including the design, conduct, or analysis of a test and its results.

international markets. The network of laboratories, organizations, people, and documents that provide assurances of the quality of electrical measurement is known collectively as the "national measurement system for electricity."[9]

1.4 TRACEABILITY

Traceability is a property of the calibration process that allows a quality control auditor to trace basic calibration values back to an appropriate fundamental standard of measurement. Hence, standards traceability is analogous to a pedigree.[10] Ideally, this pedigree is international. That is, ideally, a calibration value is agreed to by international consensus so that scientific and industrial transactions between nations can be made with confidence that the basis for measurement is consistent.

As shown in Figure 1, the international traceability hierarchy begins with international consensus under the Treaty of the Meter. The volt, along with other key units of electrical measurement, is *defined* by a consensus of the International Committee for Weights and Measures (CIPM).[11] The CIPM establishes, maintains, and disseminates the International System of Units (SI) through its deliberations. The "meter," for example, is a SI unit, as is the volt. SI *definitions* are stated without uncertainties.[12] To make use of these definitions, however, requires a physical artifact or an experimental apparatus to generate a useable *realization* of the defined unit. Such *realizations* are generally carried out in National Metrology Institutes, such as the National Institute of Standards and Technology and similar agencies around the world

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9 N. Belecki, et al, *The National Measurement System for Electricity*, (NBSIR 75-935), National Bureau of Standards, September 1978

10 The *International Vocabulary of Basic and General Terms in Metrology* (1993) defines traceability as, "The property of the result of a measurement or a value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons, all having stated uncertainties." Quoted in *NIST Calibration Services Users Guide, 1998* (SP 250), NIST, USGPO, 1998, pg. 3.

11 The CIPM oversees the activities required under the Treaty of the Meter, to which most technology advanced countries are signatories.

12 For example, the base unit of electricity, the ampere, is *defined* as follows: "that constant current which, if maintained in two straight parallel conductors of negligible cross-section, and placed 1 meter apart in a vacuum, would produce a force equal to 2 x 10-7 newtons per meter of length between these conductors."

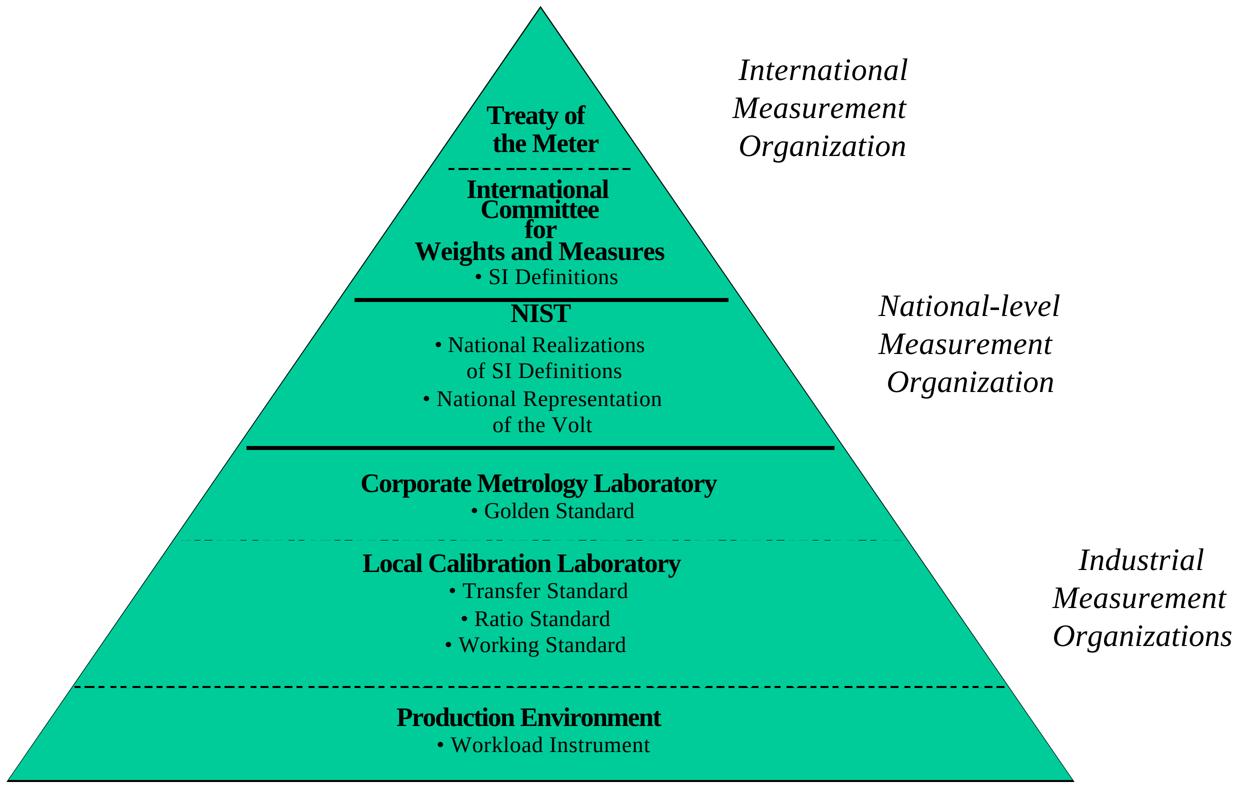

Figure 1. The International Traceability Hierarchy[13]

National traceability, in turn, involves a functional hierarchy of measurement instruments or artifacts at various "distances" from the primary standard of measurement. In general, accuracy and demands for technical expertise diminish, and the number of customers served increases, as one moves down through the measurement hierarchy.[14]

At the top of the national traceability hierarchy is a *primary standard*: A primary standard is defined and maintained by some authority as the means for calibrating secondary standards. Within a national context, NIST is the ultimate authority or "owner" of the national representation of the primary voltage standard. Within a corporate context, a central metrology laboratory typically owns the primary

[13] This figure is based on “Traceability Diagram for Direct Voltage,” in, Fluke, *Calibration: Philosophy In Practice*, 1994, p. 6-7 (hereafter, Fluke, 1994); and “Typical Corporate Support Structure”, in N. Belecki, et al, *The National Measurement System for Electricity*, (NBSIR 75-935), National Bureau of Standards, September 1978, p. 24.

[14] Fluke, 1994, p. 4-7.

standard (a *secondary standard* from a national perspective), which is often referred to as a "golden standard" for internal measurement purposes.[15]

In order to transfer the accuracy base of a national primary standard to industrial organizations, a *transfer standard* is employed. A transfer standard is used to compare a measurement process, system, or device at one location or functional level with another measurement process, system or device at another location or level. NIST utilizes transfer standards in its Measurement Assurance Program (MAP). Under this program, solid state voltage output devices are precisely calibrated at NIST. These calibrated artifacts are then sent to industry where their output voltages are measured. The measurement results and the transfer standards are then returned to NIST and measured again for comparative analysis.

Within a corporate setting, transfer standards, which are measured against the corporation's golden standards, are transferred to local (perhaps divisional) quality control organizations. These transfer standards are then re-calibrated against the organization's golden standard at pre-determined intervals according to an organization's quality assurance procedures.

Ratio standards are used to obtain other values of a unit from a traceable intrinsic or artifact standard of measurement. For example, if the national representation of the volt is an output of 10 volts, and an application requires the measurement of 5 volts or 50 volts, then the standard voltage outputs must be scaled accurately. The most common scaling technique is "ratioing" the proportion of one level of a quantity to another level of the same quantity. There are no national ratio standards.[16]

Working standards are used in routine calibration and comparison procedures in the laboratory and maintained in comparison to a golden standard. Typically, this is a solid state dc voltage output device that is less accurate and reliable than the golden standard to which it is compared for calibration. Finally, *workload calibration instruments* are calibrated routinely for use in a "production environment" (i.e., outside the confines of the metrology or calibration laboratory).

Establishing NIST traceability for a production measurement implies a documentation trail leading from a workload instrument that has been calibrated through a series of working standards and

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[15] As explained further in section 2.1.3, the situation in the case of voltage standards is somewhat more complex. Due to technology transfer efforts by NIST, several industry-level organizations own primary standards that are as accurate as the national primary standard.

[16] The instruments used to derive ratio standards in metrology labs are known as "dividers." Fluke, 1994, p. 9-3.

transfer standards and ultimately to a primary standard of measurement maintained by NIST. The pinnacle of this system is the Electricity Division of NIST's national measurement laboratory in Gaithersburg, Maryland.

1.5 HISTORICAL ROLE OF NIST IN VOLTAGE MEASUREMENT AND CALIBRATION

NIST's involvement with the development and maintenance of the standard volt can be described in three eras: the Weston Standard era; the Early JVS era; and the 10 volt JVS era. This focus of this economic impact assessment is the last of the three eras. A brief review of the preceding history of voltage measurement technology provides context. In this regard, Figure 1 depicts some of the more important technical and legal developments in the history of NIST’s involvement with voltage measurement.

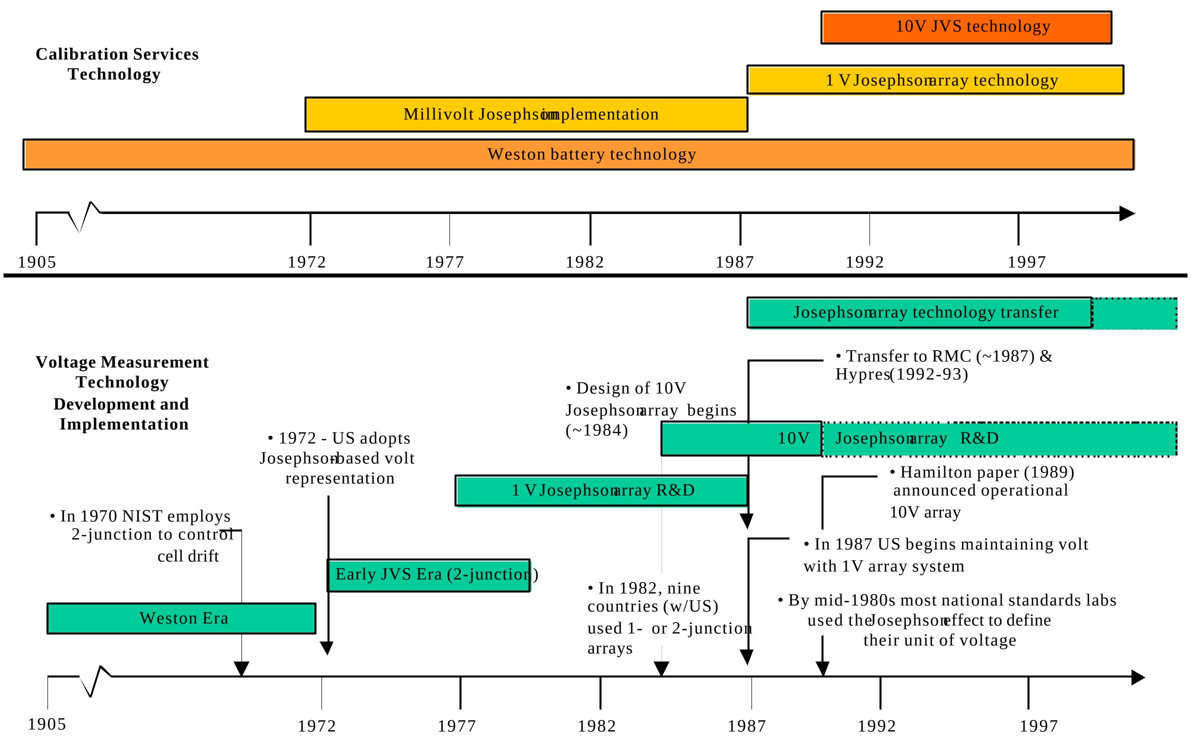

Figure 2. Development of NIST Voltage Measurement and Calibration Technology

1.5.1 Weston Standard Era

NIST was established as the National Bureau of Standards (NBS) in 1901 when voltage measurement technology was undergoing a change in battery technology—from the Clark cell to the Weston cell.[17] In1905, the U.S. adopted a new representation of the standard volt based on values derived from a bank of Weston cells located at NIST. This Weston Standard era for maintaining the national representation of the volt lasted until 1972.

1.5.2 Early JVS Era

The Early JVS Era began with collaborative efforts by researchers at the University of Pennsylvania and NIST to measure precisely the relationship between voltage (V) and frequency (F) in recently discovered superconductor devices called Josephson junctions. In 1969, University of Pennsylvania researchers published an important paper concerning the electrical properties of solid state, cryogenic Josephson junctions. Their research resulted in the first high-precision measurements of the Josephson constant (2e/h), and necessitated the construction of special instrumentation and the initiation of a special effort, both at NBS and the University of Pennsylvania, to verify the accuracy of the University's voltage standards. With this measurement in hand, it was recognized throughout the world that a precision intrinsic voltage standard was possible.[18] One of these researchers went to NIST to pursue this possibility.[19]

At that time, the U.S. representation of the volt was maintained by a series of specialized batteries called Weston cells. As a result of the research conducted in this era, NIST overcame certain inherent difficulties in using Weston cells to maintain the value of the volt, especially their variation with time (i.e., drift), severe dependence upon temperature, and occasional unpredictable abrupt voltage changes.[20] In 1972, the U.S. adopted a representation of the volt based on the electrical properties of a superconductor component called a Josephson junction device. It was designed and implemented by metrologists at NIST.

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[17] For a detailed discussion of the technical pros and cons of these two battery technologies, see, W.J. Hamer, "Standard Cells: Their Construction, Maintenance, and Characteristics," NBS Monograph No. 84, January 15, 1965.

[18] B. Field, et al, *Metrologia*, "Volt Maintenance at NBS via 2e/h: A New Definition of the NBS Volt," Vol. 9, pp. 155-166, 1973.

[19] S. Kaplan, "The Josephson Primary Voltage Standard: A New Voltage Calibration System With 5 ppm Uncertainty," CAL LAB, March-April, 1995.

[20] B. Field, et al, "Volt Maintenance at NBS via 2e/h: A New Definition of the NBS Volt," *Metrologia*, Vol. 9, pp. 155-166, 1973; and N. Belecki, et al, "Guidelines for Implementation the New Representation of the Volt and Ohm Effective January 1. 1990," NIST Technical Note 1263, June 1989.

At the international level, the consistency of U.S. voltage standards with those of other countries continued to require the inter-comparison of Weston cells. These were sent, every three years, to the Bureau International des poids et mesures (BIPM) in Paris, France.[21] However, the uncertainties attributed to such cell transfers were an order of magnitude worse than those attained when standard cells were disciplined by Josephson arrays. Thus, international agreement on the value of the volt could be improved by an order of magnitude by developing a JVS standard that could be transported for intercomparison with JVS standards sent from other countries. Such a JVS would similarly improve agreement between NBS-maintained primary standards and primary standards maintained at other domestic metrology laboratories.

By the mid-1980s, the national standards laboratories of most major industrialized countries used the Josephson effect to define their unit of voltage and maintain it constant in time.[22, 23]

1.5.3 10 Volt Josephson Standard Era

Ten years of NIST research culminated in 1987 with the implementation of a new one- volt Josephson array system to maintain the U.S. legal volt.[24] Since 1987, NIST had supported U.S. industry's transition to a new internationally agreed upon value for the volt, and continued to develop its voltage calibration technology and transfer it to industry.

Meanwhile, NIST's Josephson Volt standard researchers envisioned a relatively low cost and portable technology to improve the way that the metrology community conducts routine calibration.[25] This vision resulted in continued NIST research that came to fruition in the following results:

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[21] The BIPM carries out technical work for the CIPM depicted in the international segment of Figure 1.

[22] In 1982, the following countries utilized single junction and two-junction Josephson arrays to represent the volt: US, UK, Australia, Italy, Russia, France, West Germany, Canada, Japan. See, A. Barone and G. Paterno, *Physics and Application of the Josephson Effect*, John Wiley & Sons, 1982, pp.350-351.

[23] Unfortunately, three countries used values of 2e/h that differed from the values specified by the international standards body and, therefore, used by the majority of nations. This inconsistency resulted in national volt representations that were both larger than the international standard, for France and Russia, and smaller than the international standard for the United States.

[24] C. Hamilton, et al, “The NBS Array Voltage Standard,” IEEE Transactions on Instrumentation and Measurement, Vol. IM-36, No. 2, June 1987. R. Steiner and R. Astalos, “Improvements for Automating Voltage Calibrations Using a 10-V Josephson Array,” IEEE Transactions on Instrumentation and Measurement, Vol. 40, No. 2, April 1991.

[25] R.F. Dziuba, B. Field, and T. Finnegan, “Cryogenic Voltage Comparator System for 2e/h Measurements,” *IEEE Transactions on Instrumentation and Measurement*, Vol. IM-23, No. 4, December 1974; and B. Field and V. Hesterman, “Laboratory Voltage Standard Based in 2e/h,” *IEEE Transactions on Instrumentation and Measurement*, Vol. IM-25, No. 4 December 1976.

- Development and implementation of a 10 volt Josephson array system at NIST, which culminated in 1990[26]

- NIST's effort to transfer 10 volt Josephson array system technology to industry, beginning in the late 1980s and continuing today.

NIST is now in the third era of developing and maintaining the volt, the "Josephson 10 Volt Standard Era." This era began with NIST's decision to maintain the standard value of the volt via the 10 volt Josephson array.[27] which displaced the one volt Josephson system technology as the national standard. Since then, NIST has provided a steady stream of technological and organizational improvements leading to:

- Increased electrical measurement accuracy

- Reduced calibration cost throughout the national measurement system for electricity

- Diffusion of advanced measurement technology to sophisticated government and industrial users, which has enabled the development and sale of electrical measurement instrumentation worldwide.

For reasons that will be explained in the following chapter, NIST's efforts to transfer its 10 volt JVS technology to government and industrial users will be the main focus of this economic impact analysis.

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[26] B. Taylor, "History of the Present Value of 2e/h Commonly Used for Defining National Units of Voltage and Possible Changes in National Units of Voltage and Resistance," *IEEE Transactions on Instrumentation and Measurement*, IM-36, No. 2, June 1987; and N. Belecki, et al, "Guidelines for Implementation the New Representation of the Volt and Ohm Effective January 1. 1990," NIST Technical Note 1263, June 1989.

[27] NIST maintains the representation of the SI volt through both 1 volt and a 10 volt Josephson voltage standard systems. See Appendix A for further explanation.

2. ECONOMIC ANALYSIS FRAMEWORK

NIST's role in the development and transfer of Josephson array technology and NIST's support to industry in providing both technical guidance and calibration services was discussed in Chapter 1. Chapter 2 establishes the framework for analyzing the economic impact of NIST's contributions.

2.1 NIST OUTPUTS AND THEIR ECONOMIC IMPLICATIONS

The historical overview in Section 1.5 shows that many outputs have been generated from NIST's Josephson Volt Standard program over a long period of time. The focus of this impact assessment is confined to just one facet of NIST's overall program. Our focus is confined to NIST efforts to transfer its 10 volt JVS system technology to metrology laboratories in the private and public sector. NIST expenditures that occurred prior to the development of the 10 volt JVS system will be considered sunk costs.[28]

Before describing NIST's efforts to develop and transfer its 10 volt JVS technology, it may be useful to described some NIST activities that are related to the 10 volt JVS technology but are not the focus of this economic analysis.

2.1.1 Primary Calibration Services & Inter-laboratory Comparisons

NIST's Gaithersburg location provides primary calibration services to about 50 customer organizations with most demanding requirements for accuracy. Many of these organizations, in turn, provide calibration services on a vendor basis. The availability of the 10 volt and one volt standards, which are typical voltage levels used throughout industry, reduce measurement errors that would otherwise occur in the process of scaling up voltage measurement from millivolt output levels.

[28] The investment in any technical innovation starts with a preexisting stock of knowledge, and the attainment of that knowledge is a sunk cost.

NIST's calibration laboratory is a co-developer as well as a user of the 10 volt JVS technology. However, the calibration laboratory does not use its 10 volt JVS system for routine voltage maintenance.[29] (See Appendix A.) Still, from 1988 to 1991, NIST's calibration laboratory incorporated the 10 volt JVS into its own operation in preparation for inter-laboratory comparisons (ILCs) that would be important to the acceptance and traceability of the JVS by other government and industry laboratories.

The ILCs were launched to assure that the increasing number of volt representations were performing consistently. ILCs provide participants with an increased degree of confidence that these complex systems are behaving properly and that they are traceable to NIST's representation. ILCs have been very successful in confirming that the accuracy of the transferred "primary" Josephson volt system standard is being maintained.[30]

2.1.2 Transfer of JVS System Technology

Beginning in the late 1980s, NIST began to transfer its one-volt and 10 volt Josephson array technology to sophisticated industry and government users. These users, with extensive consulting support from NIST, integrated NIST-produced arrays and NIST-developed software, with other equipment into Josephson volt systems. Some users acquired both the one-volt Josephson array technology and the 10 volt technology. The 10 volt technology was ultimately more useful to industry because it could be applied to more generally required measurements, such as calibrating solid state reference standards at multiple output levels and calibrating voltage measurement instruments over a wide range of voltages.

Recall from the discussion of the traceability hierarchy in Section 1.4 that the nation's "primary" standard is, by traditional definition, maintained by NIST. With transfer of JVS technology to corporate metrology labs, these organizations had direct access to, effectively, primary standards. According to an industry "rule of thumb," shortening the calibration chain should have a significant effect on improving product and process accuracy.[31] These systems were also acquired to support develop of new instruments.

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[29] For this reason, the benefits of the 10 volt JVS system to calibration service providers — through NIST's calibration laboratory — was not addressed in this impact assessment.

[30] NIST and the National Conference of Standards Laboratories (NCS) have organized 5 ILCs (in 1991, 1993, 1995, 1997, and 1999).

[31] According to this rule of thumb, accuracy declines by a factor of four each step from the primary standard. Thus, the transfer standard's uncertainty is four times worse than that of the primary standard. An instrument calibrated

U.S. Government metrology organizations were among the first to acquire JVS technology, and the first private sector firms to acquire NIST's technology were Lockheed (Missiles and Space Division), Hewlett-Packard, and Fluke. By 1995 Hypres Inc., Lockheed Martin (Astronautics Division), and Keithley Instruments had acquired NIST's JVS technology and participated in the national ILCs.

NIST transferred the technology for an integrated Josephson voltage system to Hypres Inc. in 1992-93.[32] In 1994 Hypres began to market 10 volt Josephson array chip technology, and in 1996 Josephson array system technology became available commercially.[33] Hypres has sold five such systems, including one to Wiley Laboratories and one to the Boeing Company. Today, at least 16 Josephson array systems are in operation in the United States:

- Six at NIST[34]
- Nine in other U.S. government laboratories (DoE National Laboratories (2), U.S. Air Force Primary Standards Lab, NASA (3), U.S. Army, Naval Aviation Depot, Mid-Atlantic Regional Calibration Center)
- Seven in commercial standards laboratories (Boeing, Fluke, Agilent (formerly Hewlett-Packard), Hypres, Keithley, and Lockheed Corp. (2)).[35]

2.2 AFFECTED ORGANIZATIONS

2.2.1 Government & Industry Metrology Laboratories

The organizations to which 10 volt JVS systems have been transferred are typically the metrology laboratories of large producers or users of sophisticated electronic equipment. In the case of government-owned JVS systems, organizations like the U.S. Army's Redstone Arsenal, or the Department of Energy's weapons development laboratories, represent the capstone of voltage standard

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by reference to the transfer standard has sixteen times (4 x 4) the uncertainty of the primary standard, and so forth. While we are not asserting that the rule of thumb is empirically sound, it suggests that substantial benefits should accrue to owners of JVS technology in terms of the costs of maintaining a high level of accuracy within their organizations.

[32] Following IBM's decision to abandon its substantial Josephson junction research in the mid-1980s, Hypres Inc. was founded by a former IBM scientist.

[33] Personal communication with NIST, December 1998.

[34] The six systems referred to are conventional and compact 10 volt JVS systems. NIST also maintains two programmable one volt JVS systems. Personal communication with NIST, November 29, 1999.

[35] There are approximately as many JVS systems in operation in other nations.

traceability across large organizations with complex electronic maintenance and quality control systems. In addition to the needs of their own organizations, the Army's Redstone Arsenal, for example, is required by foreign governments to whom it sells sophisticated weapon systems to maintain the highest international standards of quality control.[36] Table 2 identifies owners of the NIST-developed 10 volt JVS systems as of 2000.

Table 2. JVS Owners

Commercial	Government
Agilent	DoE (Sandia National Laboratory)
Boeing Metrology Laboratory	NASA (Ames Research Center)
Fluke Corp.	NASA (Jet Propulsion Laboratory)
Hypres Inc.	NASA (Kennedy Space Center)
Keithley Instruments	U.S. Air Force (Primary Standards Laboratory)
Lockheed Martin (Astronautics Div.)	U.S. Army (Redstone Arsenal)
Lockheed Martin (Missiles & Space Div.)	U.S. Navy (Primary Standards Laboratory)
Unisys Government Systems	U.S. Navy (Mid-Atlantic Regional Calibration Center)

Similarly, among commercial owners of 10 volt JVS systems, an organization's central metrology laboratory has typically been responsible for the transfer and use of the JVS. Like government owners, commercial owners use the systems to develop new product features and to maintain high standards of measurement quality control. The commercial owners of 10 volt JVS systems consists of manufacturers of voltage source and voltage measurement instruments, including the sole commercial manufacturer of 10 volt Josephson voltage system technology, Hypres Inc. In 1992, NIST began to transfer the technology for the 10 volt Josephson array system to Hypres, Inc., which began commercial sales of Josephson array systems in 1996.[37] The Hypres Josephson volt system is pictured in Figure 3.

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[36] Many governments insist on doing business ISO 9000 registered suppliers. In the case of the U.S. Army, Redstone Arsenal is responsible for the Army-wide quality system.

[37] Personal communication with Dr. Yi-hua Tang (NIST), December 1998. Actually NIST's initial technology transfer efforts began in late 1987 with a now-defunct company, RMC Inc.

Figure 3. Hypres Inc.'s Josephson Volt System

The supply chain for electrical measurement technology of which 10 volt JVS users are a part is shown in Figure 4.

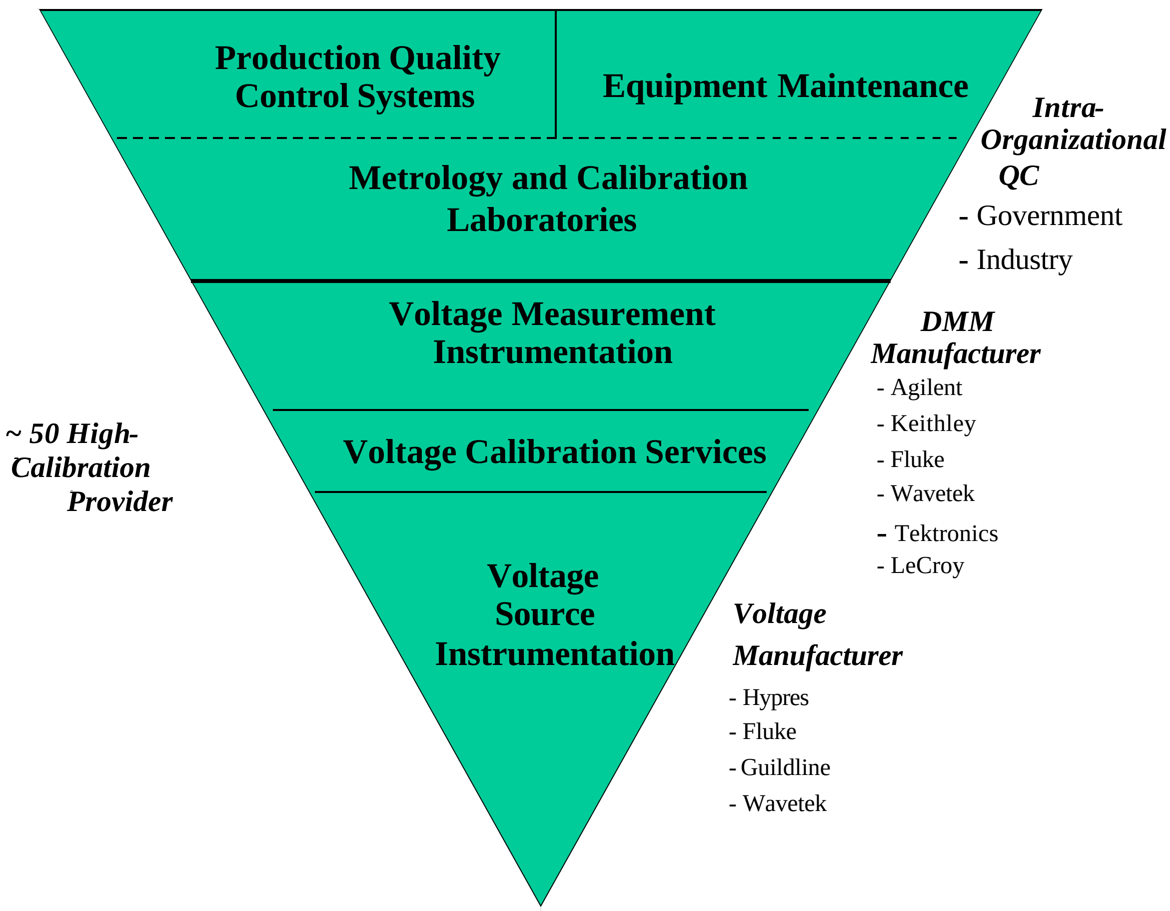

Figure 4. Supply Chain for Voltage Measurement Technology

In addition to Hypres Inc., the first tier of the supply chain also includes manufacturers of what the industry refers to as voltage source "standards." The worldwide market for all voltage output instruments is estimated at $60-100 million annually, and has been dominated by just three firms: Fluke Corporation, Wavetek Corporation, and Guildline Instruments.[38] These companies manufacture high-accuracy solid state voltage sources that are used as "golden" and transfer standards by electronic test and measurement equipment manufacturers. Fluke and Wavetek are also the principle manufacturers of multifunction calibrators.

These source and calibrator instruments are utilized for production and quality control within the first tier of the supply chain. They are also utilized widely by calibration service providers in the second tier of the supply chain, as well as in the manufacture and quality control processes of third-tier voltage measurement manufacturers.

The second tier in the supply chain is comprised of about 50 organizations that provide high-accuracy voltage calibration services commercially.[39] The annual value of all voltage calibration services (not just the highest accuracy services) may be as high as $2 billion worldwide. Domestically, the annual value of these services is estimated at $600 million.[40] Presently, it is unclear what fraction of these markets requires calibration services with accuracies at the level provided by NIST's Josephson volt system technology.[41] The voltage source manufacturers (the first-tier of the supply chain) provide a significant share of these services through networks of service centers that each maintains, thus showing a degree of
vertical integration. Additionally, many of the large aerospace and defense contractors have established large, well-equipped, and well-staffed "primary" standards laboratories. Most of these sell services to customers outside the parent company.[42]

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[38] Wavetek Inc. merged with Fluke Corp. in 2000.

[39] We estimate that there are approximately 350 calibration service providers domestically. This estimate is derived from "Laboratories and Capabilities," pp. 42-81, *A Directory of Standards Laboratories, 1999-2000 Edition*, (National Conference of Standards Laboratories). NIST provides calibration services to approximately 50 of these organizations. We assume that these 50 represent the majority of organizations that provide the highest accuracy calibration services.

[40] This is a single point estimate in need of refinement. The U.S. Census of Services does not provide sufficient detail to derive such an estimate on the basis of published data.

[41] We are currently communicating with NCSL and NIST to arrive at an approach to segmenting the calibration services tier of the supply chain. Approximately 50 of these labs rely on NIST calibration services. Some multiple of these is the likely "high-accuracy" segment that will be our focus.

[42] Fluke, 1994, p.6-9.

At the third level of the supply chain are the producers of precision voltage measuring instruments that are often used as transfer standards, working standards, and workload instruments. Such equipment measures the parameters of an incoming voltage signal. In particular, digital voltmeters are dependent on high-accuracy voltage calibration.

The world market for digital voltmeters is estimated at ~$400 million. Only a small fraction of these instruments require the high-accuracy calibration technology that derives from NIST.[43] Market leaders for voltage measurement devices include Agilent (Hewlett-Packard), Keithley, Fluke, Wavetek, Tektronix, and LeCroy. Table 3 provides estimates of the distribution of these voltage measurement instrument sales across broad user sectors.

Table 3. User Market Shares for Voltage Measurement Instruments[44]

Using Sector	Percent Voltmeter Sales
Communications	24
Industrial Electronics	20
Military & Aerospace	12
Computer & Business	8
Transportation	8
Consumer Electronics	8
Semiconductor Mfg.	4
Medical & Pharmaceutical	2
Other (e.g., utility companies)	15

The fourth and final level of the supply chain includes the users of equipment that require voltage measurement as part of normal operations. Among the most sophisticated users of voltage measurement instruments are aerospace companies and defense contractors. As explained above, government organizations are also users of sophisticated voltage measurement equipment. As depicted in Figure 4, above, within large manufacturing and system maintenance organizations, there are likely to be several "consumers" of high-accuracy voltage metrology: the central metrology laboratory; local calibration laboratories; equipment maintenance organizations; and local production organizations responsible for quality control.

[43] We are currently communicating with NIST to establish a basis for making this determination. We believe that the solution will revolve around "manufacturers specified accuracies." Whether a systematic source of such information is available is being explored.

[44] These estimates were provided by Wampler & Associates, 1999.

2.2.2 Industry Conduct

The domestic industrial suppliers of electronic test and measurement instruments in all levels of the supply chain are strongly oriented toward international markets. In 1999, the industry sectors to which these firms belong are expected to post a $3 billion trade surplus.[45] According to the Security and Exchange Commission (SEC) filings of leading instrument manufacturers, a significant share of annual revenue is generated from exports. The importance of the export market is reflected in the international marketing alliances that leading competitors have made over the past decade.

In addition to their international trade motivations, voltage instrument manufacturers' market strategies are driven by the following trends:

- Growing device complexity and electronic content in a broad spectrum of products and services
- Increasing reliance on mission critical electronic systems
- Decentralization of electronic systems
- Increasing need for companies to improve quality, document compliance with regulatory or industrial standards, and maintain a safe working environment, as required, for example, in ISO 9000
- Movement of quality control techniques from off-line sampling to in-line control
- Minimization of development time
- Pursuit of cost reductions throughout the product design process.[46]

These trends have guided the product/service development and marketing strategies of leading firms.

NIST's strategy in developing and transferring its JVS technology appears highly complementary to these industry trends. Clearly, the major focus of NIST's program, in both its system development and calibration services thrusts, has been to support the highest worldwide standards of

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[45] *U.S. Industry & Trade Outlook '99*, McGraw-Hill, 1999, Table 23-1, "Industrial and Analytical Instruments (SIC 382) Trends and Forecasts," p. 23-1, 23-4.

[46] These trends were identified in the SEC 10K reports of leading voltage source and measurement instrument manufacturers: Keithley, Wavetek, Hewlett-Packard, and Fluke.

accuracy. NIST's strategy of developing portable and stable JVS systems, to assure easy access to the highest accuracy base, appears consistent with both the increasing electronic content of manufactured systems and the decentralization of electrical systems.[47] In addition, instrument manufacturers report that NIST's JVS technology has contributed significantly to the timely development of high-accuracy voltage measurement technology.

2.3 MARKET BARRIERS AND FRICTIONS

From an economic perspective, several factors have contributed to underinvestment by the private sector in the electronic metrology technology discussed here. Such underinvestment is caused by what economists refer to as market barriers and frictions. These factors, in turn, can lead to market failures, the principal economic rationale for public investment in technology infrastructure.[48]

NIST has long has a public mandate to establish standards for electrical measurements. From an economic perspective, NIST serves this function because of the high public good content of the underlying infratechnology.[49] One of the chief requirements of effective standards is the thorough characterization of the underlying artifact, process, or method and the broadest possible diffusion of this information. The more freely these details are shared, the more effective the standards employing the infratechnology. Because of their needs to appropriate the fruits of their investments, private sector firms typically have few incentives to provide free access to their technology, especially when the cost of establishing the capability are high. Hence, public sector organizations are charged with the responsibility for maintaining standards of electrical measurement.

A second, related, reason for the primacy of public investment in basic voltage metrology is the nature of the infratechnology in question. According to Tassey, "infratechnologies" not only have common use characteristics (including their use as standards), but they often derive from a different science and generic technology base than the core technology being developed by internally funded

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[47] For early articulations of these goals, see R. Dziuba, B. Field, and T. Finnegan, "Cryogenic Voltage Comparator System for 2e/h Measurements," *IEEE Transactions on Instrumentation and Measurement*, Vol. IM-23, No. 4, December 1974; and B. Field and V. Hesterman, "Laboratory Voltage Standard Based in 2e/h," *IEEE Transactions on Instrumentation and Measurement*, Vol. IM-25, No 4 December 1976.

[48] Noll, R. G., "Economic Perspectives on the Politics of Regulation," in *Handbook of Industrial Organization, Vol. II*, R. Schmalensee and R. Willig (Eds.) Elsevier 1989, pp. 1253-1287.

[49] G. Tassey, *The Economics of R&D Policy*, (Quorum Books) 1997, p. 175.

industrial R&D.[50] This was almost certainly the case with the Josephson volt standard. The research that led to implementation of the Josephson effect as the basis for the legal representation of the volt was very basic and exploratory in nature. The technical risks involved in these undertakings undoubtedly resulted in formidable barriers to private sector investment.[51]

Market frictions are said to exist when buyers and sellers of products experience difficulties in assessing the quality or compatibility of products. To mitigate these frictions, market participants incur what economists refer to as "transaction costs:" the cost of finding parties with whom to trade, the costs of writing contracts and policing agreements, and the cost of bargaining.[52] The maintenance of the U.S. representation of the volt dramatically reduces transaction costs that would otherwise be involved in the buying and selling of sophisticated electronic goods and services. While this is generally true of NIST's involvement in the traceability process, it is exemplified in the case of voltage standards by the government's role as a buyer and regulator of products and services whose quality could have important public consequences. For example, the government is the buyer and seller of sophisticated military equipment and demands that it be maintained to the highest national standards. This functionality, in turn, depends on the maintenance of *traceable* performance by technologically sophisticated aerospace contractors and government metrology laboratories.

For consumers and producers of voltage source and measurement instruments, as well as consumers and vendors of high-accuracy calibration services, the availability of high-quality, independent, calibration capability has certainly reduced the transaction costs that would otherwise have slowed the pace of market activity. According to manufacturers of both voltage sources and voltage measurement instruments, NIST's capability has been critical to

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[50] G. Tassey, "R&D Trends in the U.S. Economy: Strategies and Policy Implications," Planning Report 99-2, Program Office, Strategic Planning and Economic Analysis Group, National Institute of Standards & Technology, U.S. Department of Commerce, April 1999, p. 40.

[51] The only alternative source of the JVS technology of which we are aware came from other national laboratories—particularly the German national laboratory, the PTB. The German PTB and NIST perceived themselves to be engaged in a technical competition with national technological prestige at stake. (Personal communication with C. Hamilton, January 1999) Over time, other nations' have implemented JVS technologies as well but none are believed to have gone as far as NIST in developing a practical, transportable, and transferable technology.

[52] Williamson, Oliver, *The Economic Institutions of Capitalism,* The Free Press, 1985, pp. 18-19.

manufacturers in testing the stability of new instrument designs and in maintaining production quality control.[53]

Finally, early in the history of the Josephson volt standard program, NIST became a source of highly specialized know-how in the relatively new field of Josephson junction applications. NIST's expertise concerning metrological applications of Josephson junction technology enabled dissemination efficiencies for public technology goods compared with distributed private sector investment. This was not a permanent government role. As market acceptance expanded, the private sector was capable of taking over NIST's technology diffusion function. NIST has actively transferred its system infratechnology to Hypres Inc. over the past decade.[54]

2.4 ASSESSMENT FRAMEWORK AND APPROACH

2.4.1 Hypothesized Outcomes

Table 4 summarizes our hypotheses about the nature of the economic barriers that have been at work in the market for the most sophisticated voltage output and voltage measurement products and services. Table 4 also identifies the beneficiaries of NIST's technology, the benefits expected to be realized by users, and the comparison scenario against which economic benefits are to be measured. From an economic perspective, NIST's 10 volt JVS transfer program was established to mitigate these barriers and compensate for the under-investments in this socially valuable technology. The conceptualization of the economic benefits of NIST's investments are derived from a concrete understanding of how industry would have behaved, and how the products and services of industry would have performed, in the absence of NIST's efforts.

[53] Personal communication with Agilent (Hewlett-Packard), March 3, 1999; Keithley, April 2, 1999

[54] Actually NIST technology transfer efforts began in late 1987 with a now-defunct company, RMC Inc. RMC was not interested in acquiring Josephson array fabrication technology. The German national standards lab, PTB (Physikalisch-Technische Bundesansalt) pursued a similar technology transfer strategy with the German firm, Prema. PTB's 10 volt Josephson standard technology was not available for sale or transfer until 1996. (Personal communication with PTB, March 12, 2001.)

Table 4. Working Hypotheses: Barriers, Outputs, and Benefits

Market Barriers	Related NIST Outputs	Hypothesized Outcomes	Beneficiaries	Benefit Measures	Comparison Scenario
Infratechnology *Concentration of specialized know-how at NIST*	10V JVS technology Technical expertise	Enabler of new measurement instrument designs (esp. linearity of ADCs for "high-end" digital multi-meters (DMMs) and multifunctional calibrators (MFCs)) Metrology/QC process efficiencies Frequency of calibration increases	JVS system owners	Profit margins on sales of instrumentation that would have been delayed Product development cost savings Product time-to-market savings Total metrology/QC budgets Scrape & re-work cost savings	Adopting technology through in-house efforts or through German PTB

2.4.2 Comparison Scenario

As described in Section 1.5 above, NIST was consciously engaged in a race for the development and application of the Josephson effect to voltage measurement problems with other national laboratories. From the historical record it appears that the German national standards laboratory — Physikalisch-Technische Bundesansalt (PTB) — was the closest to developing an applicable 10 volt Josephson system that could be viewed as a substitute for NIST's JVS. It is certainly conceivable that private sector voltage instrument manufacturers or universities might also have filled the niche had NIST not made the investments that led to the JVS. On the basis of these observations, and interviews with industry representatives, user benefits are estimated in comparison to a counterfactual scenario that posits a time gap between the year in which the users' JVS system became operational and the time substitute technology — developed in-house or purchased from the German PTB — would have been available. Survey respondents typically identified PTB as the source of alternative technology, if it had not been available from NIST. PTB's 10 volt Josephson technology was first sold in 1996.

2.4.3 Impact Estimation Timeframe (1987-2000)

The timeframe for assessing the costs and benefits of NIST's 10 volt JVS technology transfer program begins with the development and initial fabrication of a 10 volt Josephson arrary, in 1987, and ends in the year of the assessment survey, 2000. NIST's program costs, user organizations' "pull costs," and estimates of users' economic benefits are available for this period based on NIST's records and the results of a survey of 10 volt JVS system owners designed and implemented as part of this impact assessment.

3. SURVEY FINDINGS

3.1 SURVEY POPULATION AND SAMPLE

All Government- and private-sector metrology laboratories that employ a 10 volt JVS were contacted through an iterative e-mail and telephone survey. The survey population is depicted in Table 3 of Section 2.2.1 above. A number of respondents did not provide sufficient information to be useful in either the qualitative or quantitative aspects of the impact assessment. Three organizations declined to participate — two manufacturers and two government laboratories. Survey respondents are shown in Table 5 along with the year their 10 volt JVS systems became operational. During the course of the survey it was discovered that multiple NASA metrology laboratories share a "portable" JVS system. Few of these labs provided sufficient quantitative information to appreciably affect the economic impact estimates.

Table 5. Survey Respondents and Year of JVS Implementation

JVS Owners	Year Operational
Commercial	
Lockheed Corp. (Missile & Space Div.)	1987
Agilent Inc. (Hewlett-Packard)	1988
Fluke Inc	1991
Keithley Inc.	1992
Boeing Company	2000
Government	
U.S. Navy/NAVAIR	1988
U.S. DoE	1991
U.S. Army/Redstone	1992
U.S. Air Force	1996
NASA/WSTF	1997
NASA/KSC	1997
NASA/Ames	1997
NASA/Stennis	1998
NASA/JSC	1998
NASA/JPL	1998

3.2 QUANTITATIVE FINDINGS

Survey respondents provided estimates of four categories of benefits attributable to the transfer and implementation of NIST technology: benefits related to equipment cost savings, labor cost savings, external failure cost savings (warranty, scrap, rework, re-test), and sales revenues that would not have materialized had they not owned a 10 volt JVS system.

The estimates were the product of a three-part analysis process in which respondents were asked to assess:

- Technical consequences and associated costs of maintaining the highest possible level of measurement quality in the absence of 10 volt JVS technology
- Annual costs to maintain such an alternative system (economically and technically)
- Cost comparisons of the actual and counterfactual system implementations.

The difference between the total cost of maintaining their own JVS system and the total cost of operating an alternative approach to voltage metrology is the estimate of the annual benefit attributable to the JVS technology from the NIST infratechnology.

A relatively important source of benefits to the commercial sector has been the sale of sophisticated voltage measurement equipment that industry representatives assert would not have been available to the market were it not for the 10 volt JVS technology. Roughly speaking, this category of benefits accounts for 78% of all benefits in the period (1992 – 1995) where benefits were the largest and were realized in all four benefits categories. Industry representatives claim that high-end voltage measurement equipment with high levels of accuracy and precision would not have been possible were it not for the JVS technology that allows the linearity of their measurement systems to be tested and verified.[55]

These estimated benefits were only attributable to NIST so long as an alternative source of 10 volt JVS system technology was not available. PTB's substitute technology would have been available in 1996. The annual benefits estimated by respondents were only credited to NIST for the years

[55] Generally speaking, "linearity" refers to a directly proportional (i.e., "straight line") relationship between two variables. Linearity error is an important concern for voltage source and measurement manufacturers and users. Liner instrument response is typically specified. In simple terms this means, for example, that if one doubles an instrument's input signal, the device that records that change of input records a doubling of the device reading.

between the year in which the respondents' JVS became operational and 1996. This empirical decision makes the resulting benefit estimates conservative because attributing some portion of the post-1996 benefits to NIST could have been justified. Also, where respondents identified sales revenue that would not have been available in the absence of a 10 volt JVS system, only the value added (estimated profit margin) on the pre-1996 sales was claimed as part of the benefit stream attributable to NIST's investments.

3.3 QUALITATIVE FINDINGS

There seems to be a significant difference between what might be called a product development perspective concerning NIST's 10 volt JVS technology and a calibration services perspective. From the product development perspective, NIST's JVS technology transfer program was fundamental. Manufacturers of sophisticated voltage measurement instrumentation have benefited the most from this technology. Their estimates dominate the benefit stream used to calculate the economic impact of NIST's investments. According to one industry representative, "I was not aware of an alternative to the JVS system at *any* cost [emphasis added]. Without an on-site JVS system we could not have developed the [high-end instrument] with the specs it has, and a reduced spec product might have been delayed for several years." Another manufacturer of a voltage measurement instruments remarked, "The technical development by NIST was crucial to us having a JJ system here."

The linearity of the A/D converters in their instruments was essential to the development and sale of new sophisticated and profitable voltage measurement instruments. The JVS system enabled manufactures to evaluate their products at a level not previously possible. With the JVS in house, error data could be provided to instrument design teams. When respondents were pressed to imagine a process by which there instrument development programs could employ external technical services to achieve the same ends, the possibility was deemed unlikely. Ownership was critical.

From a voltage calibration services perspective, on the other hand, the 10 volt JVS system is a sophisticated and technically demanding investment. The expense and technical effort needed to operate and maintain the system was commented on widely by survey respondents. Several respondents asserted that, from a calibration-services point of view, it was not worth the investment. Typically, that is, calibration services customers were not interested in achieving uncertainty levels made possible by the JVS system.

“Technological overkill” captures the sense expressed by many respondents. Even producers of very sophisticated equipment argue that the measurement quality provided by the JVS is well beyond their calibration requirements. A few respondents cited “prestige” rather than technical requirements as the primary cause of their organization’s investment in 10 volt JVS technology. They were unable to translate this prestige into economic value.

One calibration laboratory manager articulated both perspectives when he complained that he had to make the best of an expensive and difficult device that was “inherited from the product development side of the house.”

For instrument manufacturers, the JVS technology has another important economic implication. Manufacturers refer to the “prestige” associated with early market presence of “high-end” products. From an economic perspective an important facet of this prestige can be viewed as transaction cost economies. In response to questions concerning such costs, one respondent replied, “I don’t know how much effort it takes for the average sale, but after the reputation of the instrument was established, I’ll bet it doesn’t take much to sell one.”

Similarly, in response to questions concerning the value of high-end measurement instruments to their users, a manufacturer explained that, “customers will probably not know which of the [high-end instrument] specs they rely on that, in turn, rely on the JJ and which ones do not. And I'm sure some customers just buy it because it is the best you can buy, and so for performance applications it is a "safe" buy, without analyzing which features they must have, which they want etc.” In other words, by buying “too much,” users are paying a premium to compensate for the lack of knowledge required to understand their technical requirements, determine which instruments provide those requirements, and thereby acquire the knowledge needed to procure the appropriate technology.

4. QUANTITATIVE ANALYSIS

4.1 BENEFITS

Broadly speaking, two types of benefits accrued to JVS system owners as a result of the transfer of NIST's 10 volt JVS technology: cost avoidance benefits and new product benefits. Cost avoidance benefits were formulated through a comparison of actual process costs to hypothesized process costs employing less advanced measurement technology that would have been employed in the absence of NIST technology.

New product benefits are derived from estimates of profit margins on revenue from the sale of equipment whose development, according to industry representatives, depended on NIST JVS technology. Based on survey information, a factor of 20 percent represents a conservative estimate of the profit margin on sales revenue estimates provided by survey respondents.[56]

Both types of benefits were assigned to NIST only for the period of time in which no substitute for the NIST 10 volt JVS system was available. The time series of these combined benefits, in nominal dollars is presented in Table 6.[57]

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[56] Interviews with industry representatives indicate that net profits for the kind of high-end measurement instruments discussed here range between 10 percent and 30 percent.

[57] Due to the nature of the comparison scenario, most benefits occur prior to 1996. One government laboratory that adopted the JVS technology relatively late, but would not have adopted a PTB solution, estimated cost avoidance benefits for the 1997-1999 period.

Table 6. JVS Owner Benefits

Year	Annual JVS Owner Benefits (Nominal $)
1987	140,000
1988	2,400,000
1989	2,400,000
1990	2,500,000
1991	2,800,000
1992	4,000,000
1993	4,000,000
1994	4,000,000
1995	4,300,000
1996	0
1997	56,000
1998	56,000
1999	57,000

4.2 NIST EXPENDITURES & JVS OWNER "PULL COSTS"

The cost associated with the development and transfer of the 10 volt JVS system technology are of two types: NIST expenditure and the one-time costs expended by JVS system owners to acquire the technology from NIST. NIST expenditures were estimated for the two NIST organizations involved in the development and implementation of the 10 volt JVS: NIST's Electricity Division in Gaithersburg Maryland, and NIST's Electromagnetic Technology Division in Boulder, Colorado. These cost estimates consist of total compensation paid to NIST employees for efforts that contributed directly to the development, fabrication, integration, and testing of the 10 JVS system and its components.

JVS owners were asked to estimate the initial one-time costs over and above the cost of the JVS technology itself. These "pull costs" are typically expended for technical consultants, material, or research required to make the technology operational in the owner's particular setting. The time series of NIST expenditures and user pull costs, in nominal dollars, is presented in Table 7.[58]

[58] Pull costs were estimated on the basis of survey responses. Gaps in the time series of these costs reflect the timing of respondents' system implementations.

Table 7. NIST Expenditures & Owner "Pull Costs" (Nominal $)

Year	NIST Costs (Nominal $)	Pull Costs (Nominal $)	Total Cost (Nominal $)
1987	330,000	11,000	340,000
1988	410,000	85,000	500,000
1989	490,000	31,000	530,000
1990	510,000	170,000	670,000
1991	400,000	140,000	540,000
1992	390,000	180,000	570,000
1993	400,000	0	400,000
1994	410,000	14,000	430,000
1995	420,000	14,000	440,000
1996	57,000	0	60,000
1997	58,000	4,000	60,000
1998	59,000	0	60,000
1999	60,000	0	60,000

4.3 MEASURES OF ECONOMIC IMPACT

Table 8 transforms the nominal costs and benefits reported in Tables 6 and 7 into a series of constant 2000 dollars that provides the basis for the summary economic impact estimates reported below: social rate of return (SRR), net present value (NPV), and benefit-to-cost ratio (B/C).[59] (For a explanation and discussion of these metrics, see Appendix C.)

[59] The deflator used to convert to constant dollars is the Gross Domestic Product Price Index (chain type), *Economic Report of the President, 2001*, Table B7.

Table 8. Constant 2000 Dollar Benefits and Costs (1987 – 1999)*

Year	Constant Dollar Benefits ($2000)	Constant Dollar Costs ($2000)	Constant Dollar Net Benefits ($2000)
1987	190,000	470,000	-280,000
1988	3,100,000	660,000	2,400,000
1989	3,100,000	670,000	2,400,000
1990	3,100,000	830,000	2,300,000
1991	3,300,000	650,000	2,700,000
1992	4,700,000	670,000	4,000,000
1993	4,700,000	460,000	4,200,000
1994	4,700,000	470,000	4,230,000
1995	4,700,000	470,000	4,230,000
1996	0	61,000	-61,000
1997	58,000	65,000	-7,000
1998	58,000	61,000	-3,000
1999	58,000	61,000	-3,000

* The deflator used to convert current to constant dollars is the Gross Domestic Product Price Index (chain type), *Economic Report of the President, 2001*, Table B7.

Based on the time series presented in Table 8, estimates of the economic impact metrics for NIST's 10 volt JVS technology program are displayed in Table 9.

Table 9. Estimates of Economic Impact

Performance Metric	Estimate
Net Present Value in 1987	$18,700,000
Net Present Value in 2000	$45,100,000
Real Social Rate of Return	877%
Benefit-to-Cost Ratio	5

There is reason to believe that the metrics reported above understate the true economic impacts of NIST's JVS program. First, the economic impact of the JVS technology on NIST's national calibration services was not considered within the scope of this assessment. While the two programs are in many ways integral, understanding the structure of the market for calibration services — a necessary first step — would have involved research that was beyond the financial scope of the project. In addition, the 10 volt JVS system employed by NIST is used to check NIST calibration instruments. It is not used directly to calibrate the instruments of NIST's customers. Therefore, conceptualizing the benefits of the 10 volt JVS system in a manner that would be sensible to NIST's calibration services customers proved impractical. As a results, only the impact of transferred 10 volt JVS hardware and software was assessed.

Second, even within the context of the rather straightforward assessment of transferred physical assets, many respondents were unable or unwilling to respond to the counterfactual experiment posed in the survey. It is typical to receive readily available technical information but uncommon for respondents to "think through" the less obvious issues of economic impact. That several NIST customers expended the energy to do so is a credit to them and to the relationships with industry that NIST has cultivated.

Third, the sales of high-end equipment voltage measurement equipment, that figure so prominently in this quantitative analysis of economic impact, have a prestige effect that has an impact on the sales of products other than those directly related to the JVS technology. During the early years of these sales, the United States was the unrivaled source of this technology. Interviews indicate that considerable spillover prestige (i.e., good will) probably accrued to US companies offering high-end instruments to the market. Several electrical parameters derive from the volt: electrical resistance, electric capacitance, and conductance. To the extent that the instruments used to measure these parameters are different than those used to measure voltage, it is likely that some fraction of their worldwide market success is attributable to JVS technology.

Finally, industry representatives believe that "the real impact" of JVS technology is at the next tier in the supply chain — the application of JVS-enabled voltage measurement technology (DMMs and MFCs) in a production environment— where they should have a substantial impact on scrap, rework, and re-test. The ability to introduce sophisticated measurement instruments to the shop floor, in the late 1980s and throughout the 1990s, depended on the ability to calibrate and verify their performance. While industry representatives agree that these benefits are likely, they were unable to identify points of contact that could respond knowledgeably on economic impact issues.

APPENDIX A — VOLTAGE CALIBRATION AT NIST

In 1972, NIST implemented the initial Josephson volt system in place of Weston battery cells for maintaining the national representation of the volt. Yet, Weston cells are still used at NIST and in many calibration laboratories because they exhibit good voltage stability and a long, useful life. They require special environmental control (temperature-regulated oil or air bath) and can be unstable for months following unanticipated changes in their environment. In addition, even under controlled conditions, their voltage output values drift over time. This drift is one reason that the Weston cell was officially replaced by the NIST-developed Josephson system. According to one source, Weston cells are becoming difficult to obtain and are being phased out and replaced by solid state voltage output devices.[1]

The electronics calibration laboratory at NIST is similar to the calibration laboratory of any sophisticated producer or user of electrical test equipment.[2] The Weston battery cell, its electronic counterpart (solid state voltage references), and the NIST-developed Josephson volt system continue to be used in an integrated system of voltage references at NIST as well as in industry standards laboratories across the nation.

NIST maintains four tiers of voltage standards:

(1) 10 volt JVS system & one volt JVS system

(2) NIST "Primary Standards" (Weston cell banks)

(3) Working Cell Groups (Weston cell banks)

(4) Check Standards (solid state references and saturated cells)

NIST's calibration laboratory maintains many banks of Weston cells that are used for different specific functions depending on their historical performance characteristics (e.g., stability and accuracy). The two best performing banks are designated "NIST Primary Standards," which are calibrated against the one volt Josephson system on a monthly basis. The 1 volt Josephson system is also compared with

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[1] See Fluke, 1994, pp. 7-12, 7-15.

[2] NIST's calibration lab is believed to be typical of advanced electrical metrology labs. (Personal communication with NIST's Calibration Laboratory, April, 1999.)

the Josephson 10 volt system monthly to assure the long term and short term consistency of the two systems.

All the Weston cells that are not designated as "primary standards" are used as "Working Cell Groups" (WCGs) and “Check Standard Cell Groups” (CSCGs). All of the NIST solid state standards are solid state check standards (SSCSs). The WCGs are the standards used as the reference voltages in the three measurement systems. The measurement systems’ check standards are CSCGs and SSCSs and replacement WCGs are selected from the SSCSs. The three WCGs are calibrated against the NIST Primary Standard cells on a daily basis. All check standards and customer (outside) standards are calibrated against the WCGs on a daily basis. Finally, one solid state "check standard" is calibrated against the 10 volt Josephson system on a monthly basis.

Volt Calibration is managed by three measurement systems: System 1, System 2, and System 3. System 1 handles the calibration of the three WCGs and the standard cell groups that are used in NIST’s Measurement Assurance Program (MAP). NIST's Measurement Assurance Program (MAP) ships standard cell groups with known performance attributes from NIST to industrial and other government sites for in situ assessment of outside calibration laboratory equipment.

System 2 is described as "the workhorse" of the NIST calibration laboratory. It performs the normal workload of calibrating solid state and saturated cell reference standards from other NIST laboratories and outside organizations. System 3, in turn, is very similar to System 1. It provides the back-up capability necessary for routine maintenance and also supports periodic surges in the calibration workload.

APPENDIX B — ELECTRICAL METROLOGY IN PRACTICE

The Voltage Calibration Process

The calibration function entails three major tasks:

- Setup activities, which involves identifying instruments to be calibrated, determining calibration intervals, setting quality levels, documenting the location and use of instruments, establishing the kind of calibration test to be preformed and the place of calibration (on-site or in lab), and determining the skill level required to make various calibrations

- Daily operations, including transporting instruments, performing tests, taking care of and repairing test instruments, making calibration adjustments, maintaining measurement standards, and returning calibrated instruments.

- Workload management, involving activities undertaken to improve the calibration process.[1]

The quality and cost of calibration is a function of the assignment and adjustment of calibration intervals and policies under the circumstances that measurements are made.[2]

Electronic measuring devices are generally divided into “source” instruments and “measure” instruments. Source instruments provide a means of emitting an electrical signal with well-defined characteristics. Calibrating a source instrument requires the use of an equivalent measuring instrument of sufficient accuracy so that the total uncertainty is within the instrument's specification.

Similarly, measure instruments, such as a digital multimeter (DMM), are calibrated by comparison to a previously calibrated source instrument. Thus, to calibrate the voltage scales of a DMM, a DC voltage source of known output is needed. In either case, to complete the calibration process, you need a means of adjusting the instrument under calibration readings so that they match the values of the calibration standard. The crudest way to make this adjustment is with a calibration chart, in which measured values are plotted on the ordinate (horizontal) axis and the corresponding "actual" values are plotted on the abscissa (vertical) axis. When making subsequent readings using the measuring

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[1] Fluke, 1994, p. 19-3.
[2] Fluke, 1994, p. 24-3.

instrument, the user finds the reported value read from the instrument on the ordinate, and follows it up vertically until the calibration curve is reached. The user then moves horizontally to the abscissa to read off the measured value.

Most analog electronic instruments are calibrated by adjusting the gains and offsets of the various amplifiers in the instrument to bring its readings in line with the "actual" values. Depending on the particular instrument being calibrated and the uncertainty level to which it needs to be held, this is a more-or-less tedious manual operation.

The most sophisticated digital instruments have internal circuitry that applies calibration corrections before reporting readings. The measurement process is exactly analogous to using a calibration chart, except that the digital instrument performs this automatically. Thus, the calculation and application of calibration corrections is entirely invisible to the user.

The final step in calibrating an instrument is to prepare a document of relevant information about the calibration. This documentation may be as simple as affixing a calibration sticker that reports the date on which the calibration was done. More typically, additional information goes into the calibration report, such as the uncertainty level and when the next calibration is due. Calibration reports can become quite complicated, sometimes giving all of the measurements used and the results, calculations of secular drifts, etc. The amount of information required in the calibration report depends on the users' requirements.

To calibrate an electronic instrument, one must connect its terminals to those of the standard, take several readings at different levels, calculate the appropriate corrections, download those corrections into the instrument's memory (assuming the instrument has these capabilities built in) and create the calibration report.

Voltage Measurement Instrumentation: The "Production" Environment

The quality range of available measurement instruments blurs the line between the laboratory and production environments. High-end digital multimeters (DMMs), for example, can be as high in resolution and accuracy as the multifunction calibrators (MFCs) designed to calibrate them. DMMs typically measure a wide range of electrical stimulus, including direct voltage, direct current, alternating voltage, alternating current, and resistance.

There are three classes of DMMs: laboratory, bench, and hand-held. Laboratory DMMs typically provide the highest level of accuracy and resolution, approaching the accuracy of the MFC used to calibrate them. They display up to 8 1/2 digits in their readouts and are frequently calibrated automatically. Bench DMMs are very similar to the previous class but tend to have less accuracy and resolution, typically 4 1/2 or 5 1/2 digits. In many local calibration labs, the bulk of the workload is composed of bench DMMs. Handheld DMMs are the most commonly used and typically offer a wider set of measurement functions than the bench or laboratory versions. Their accuracy and resolution is typically 3 1/2 or 4 1/2 digits. Handheld DMMs tend to be used in a wide range of applications, from sophisticated electronic testing to automotive maintenance. Handheld DMMs are even used by hobbyists.

Electrical instruments and meters of all types are calibrated by adjusting their circuitry so that they report the correct value when measuring an electrical property. A DMM, for example, is comprised of a measurement section and a control section. The measurement section (made up of analog conditioning circuits and an analog-to-digital converter (ADC)) requires calibration to assure stability in its sources of variation (gain, offset, and linearity errors). Every DMM also contains a solid state dc voltage reference for the ADC. This internal reference is the limiting factor for the accuracy of all voltage and current measurements performed by the DMM. It requires calibration.[3]

[3] Fluke, 1994, pp. 17-4 - 17-18.

APPENDIX C — ECONOMIC IMPACT METRICS

Two evaluation metrics used customarily by NIST's Program Office are the internal (social) rate of return and the ratio of benefits-to-costs. A third metric, net present value, is readily derived from the information developed for the benefit-to-cost ratio.

The metrics in this report are calculated from a time series of costs and benefits in constant dollars. Therefore, "real" rates of return are presented based on this time series of constant dollars. In contrast, several previous economic impact assessments conducted by TASC for NIST's Program Office presented "nominal" rates of return that were based on time series of current dollars (the dollars of the year in which the benefits were realized or the costs were incurred).

Internal Rate of Return (IRR)[1]

The IRR is the value of the discount rate, i, that equates the net present value (NPV) of a stream of net benefits associated with a research project to zero. The time series runs from the beginning of the research project, t = 0, to a milestone terminal point, t = n. Net benefits refer to total benefits (B) less total costs (C) in each time period. Mathematically,

$$(1)\quad NPV = [(B_0 - C_0) / (1 + i)^0] + \ldots + [(B_n - C_n) / (1 + i)^n] = 0$$

where $(B_t - C_t)$ represents the net benefits associated with the project in year t, and n represents the number of time periods (years in most cases) being considered in the evaluation. For unique solutions of i, from equation (1), the IRR can be compared to a value, r, that represents the opportunity cost of funds invested by the technology-based public institution. Thus, if the opportunity cost of funds is less than the internal rate of return, the project was worthwhile from an *ex post* social perspective.

[1] The characterization of the three metrics follows Chapter 4 of Albert N. Link and John T. Scott, *Public Accountability: Evaluating Technology-Based Institutions* (Boston: Kluwer Academic Publishers) 1998.

Benefit-to-Cost Ratio

The ratio of benefits-to-costs is precisely that, the ratio of the present value of all measured benefits to the present value of all costs. Both benefits and costs are referenced to the initial time period, t = 0, as:

$$B / C = [?_{t=0 \text{ to } t=n} B_t / (1 + r)^t] / [?_{t=0 \text{ to } t=n} C_t / (1 + r)^t]$$

A benefit-to-cost ratio of 1 implies a break-even project. Any project with B / C > 1 is a relatively successful project.

Fundamental to implementing the ratio of benefits-to-costs is a value for the discount rate, r. While the discount rate representing the opportunity cost for public funds could differ across a portfolio of public investments, the calculated metrics in this report follow the guidelines set forth by the Office of Management and Budget:

> Constant-dollar benefit-cost analyses of proposed investments and regulations should report net present value and other outcomes determined using a real discount rate of 7 percent.[2]

Net Present Value (NPV)

The information developed to determine the benefit-to-cost ratio can be used to determine net present value as:

$$NPV = B - C$$

Note that NPV allows in principle one means of prioritizing among several projects *ex post*.

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[2] "Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs," Office of Management and Budget (OMB), Circular No. A-94, 29 October 1992.