

97-1 Planning Report

Economic Assessment of the
NIST Thermocouple Calibration
Program

Prepared by:
Michael L. Marx
Albert N. Link
John T. Scott

Approved by:
Leon S. Reed
David P. Leech

July 1997

Prepared for the
Program Office
National Institute
of Standards
and Technology

NIST

U.S. Department of Commerce
Technology Administration



ECONOMIC ASSESSMENT OF THE NIST THERMOCOUPLE CALIBRATION PROGRAM

July 11, 1997

Prepared for:

The National Institute of Standards and Technology
Gaithersburg, MD

Prepared under:

Contract No. GS-22F-0101B

Prepared by:

Michael L. Marx
Albert N. Link
John T. Scott

Approved by:

Leon S. Reed
David P. Leech

TASC, Inc.
1101 Wilson Boulevard
Suite 1500
Arlington, VA 22209

TABLE OF CONTENTS

	Page
EXECUTIVE SUMMARY	1
1. INTRODUCTION.....	4
1.1 NIST	4
1.2 NIST Thermocouple Calibration Program	4
1.3 Case Study Objectives.....	6
1.4 Case Study Outline	6
2. TECHNICAL OVERVIEW.....	8
2.1 Circuit	8
2.2 Types.....	9
2.3 Calibration	10
3. INDUSTRIAL OVERVIEW.....	13
3.1 Applications.....	13
3.2 Cost and Quality Drivers for Accuracy	15
3.3 Industrial Structure	17
3.3.1 Suppliers.....	17
3.3.2 Users	17
3.3.3 Infrastructure	19
3.4 Traceability of Standards.....	21
4. EVALUATION FRAMEWORK AND APPROACH.....	24
4.1 Scope	24
4.1.1 Reference Functions and Tables	24
4.1.2 Primary Calibration Services	24
4.1.3 Technical Support to Industry	25
4.2 Benefit Measures	26
4.3 Comparison Scenarios.....	27
4.4 Benefit Data.....	28
4.2.1 Survey of Thermocouple Users	28
4.2.2 Survey of Thermocouple Suppliers.....	29
5. SURVEY RESULTS	30
5.1 Thermocouple Users	30
5.1.1 Calibrations Performed Internally	30
5.1.2 ISO 9000	31
5.1.3 ITS-90	32
5.1.4 Transactions costs.....	33
5.1.5 Other	33

5.2	Thermocouple Industry	34
5.2.1	Wire Suppliers	34
5.2.2	Thermocouple Suppliers.....	35
5.2.3	Summary.....	36
6.	ECONOMIC ANALYSIS	38
6.1	Cost and Net Benefit Data	38
6.1.1	NIST Annual Expenditures and Income.....	38
6.1.2	Data for economic impact analyses.....	39
6.2	Measures of Economic Impact	40
6.2.1	Internal Rate of Return.....	40
6.2.2	Adjusted Internal Rate of Return.....	41
6.2.3	Benefit-cost Ratio	42
6.3	Measure of Economic Importance.....	42
6.4	Economic Return on Upgrade of Reference Tables to ITS-90	43
6.4.1	International Conformity to the Temperature Scale.....	44
6.4.2	Other Temperature Measuring Devices	44
6.4.3	Long-Term Benefit Horizon.....	45
6.4.4	R&D Leadership Role.....	45
7.	CONCLUSIONS	47
7.1	Economic Importance of Thermocouples	47
7.2	Economic Impact of the NIST TCP	47
7.3	Potential Improvement in the Traceability Process.....	49
7.4	Lessons-Learned from Implementing ITS-90.....	50

LIST OF FIGURES

Figure		Page
2-1	Basic circuit for thermocouple thermometry	9
3-1	Sample Applications of Thermocouples by Common Requirements of Uncertainty.....	14
3-2	Traceability Paths for Thermocouple Calibration Standards	22

LIST OF TABLES

Table		Page
6-1	Expenditures and Income for the NIST TCP FY 1990-1996 (current \$).....	38
6-2	NIST TCP Costs and Net Industry Benefits (current \$000).....	39

EXECUTIVE SUMMARY

The National Institute of Standards and Technology (NIST) assists industry in the development and promulgation of standards for the calibration of thermocouples. The primary purpose of this case study is to evaluate the economic impacts on domestic industry for investments made in this infrastructure technology through the NIST Thermocouple Calibration Program (TCP).

Thermocouples are electronic sensors for measuring temperature for use in a wide variety of applications (e.g., medical procedures, scientific research, automated manufacturing processes, and consumer products) where temperature is an important parameter in a measurement or control system. The annual sales of thermocouple products sold by the domestic thermocouple industry (suppliers of wire and thermocouple assemblies) into the U.S. market is 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 \$81.0 billion. The demand for thermocouples is expanding because of their importance for computerized instruments, which are used increasingly for the monitor and control functions in manufacturing applications to improve corporate productivity. Therefore, thermocouples have a significant effect on the current and future competitiveness of U.S. industry.

The NIST TCP generates technical knowledge to improve the calibration accuracy and efficiency of thermocouple measurements made in industry. This case study focused on three technical outputs: (1) reference functions and tables for letter-type thermocouples, (2) primary calibration services for traceability of standards used in thermocouple measurements, and (3) technical support to industry. In particular, standards traceability provides an efficient means for ensuring accurate measurements across divergent industrial environments, and NIST is the pinnacle of the traceability structure for national standards linked to international agreements of temperature scale. Establishing a process for documenting the accuracy of temperature measurements to national temperature standards is an essential element in meeting ISO 9000 certification, which is necessary for marketing products internationally. The standards traceability process through the NIST TCP provides thermocouple users with an efficient means to comply with the requirements of ISO 9000 since the burden-of-proof for documented compliance can be obtained from the wire or thermocouple supplier.

From the technical outputs of the NIST TCP, thermocouple users and suppliers derive three main types of benefits: (1) efficiencies in developing and disseminating the technical knowledge needed for performing thermocouple calibration tests, (2) transactions cost savings between users and producers engaged in thermocouple commerce, and (3) improved competitiveness for users of thermocouples through enhanced product performance and process efficiency. In this case study, the first two types of benefits were estimated while the third type of benefit proved to be difficult to quantify. Yet, from a national competitiveness standpoint, the economic magnitude of the latter benefit type is significantly greater than the first two benefit types.

The internal rate of return (IRR) from investments in the NIST TCP has been calculated to be at least 31.8 percent. A number of factors have been incorporated in this calculation to portray this as a conservative, lower-bound estimate of NIST's economic impact on domestic thermocouple users and suppliers. This estimate is based on appraisals of economic benefits and expenditure data related to the outputs of the NIST TCP. Net benefits have been estimated from a survey of the domestic thermocouple industry using a hypothetical, counterfactual experiment. The resulting 31.8 percent IRR implies that the NIST Thermocouple Calibration Program is pursuing a socially-valuable activity affecting a broad range of domestic industries.

Many thermocouple users having requirements of high accuracy rely on calibration tests performed internally rather than from statements of accuracy obtained from their suppliers. These users claim that internal calibration testing is both necessary due to the inconsistent nature of thermocouple calibrations and an efficient means of maintaining process control with applications having stringent accuracy requirements. However, to some extent, the efficiency in the standards traceability scheme headed by NIST is being degraded since users cannot rely totally on their suppliers to provide the correct representations of calibrations for thermocouple products. The root cause of this non-optimal situation appears to derive from issues about assurances of product quality from suppliers of wire and thermocouples, and these issues are not linked directly with measurement-related know-how from the NIST TCP. However, NIST could use its neutral role to help industry overcome this problem so that the implementation of the traceability process can approach greater efficiency.

The survey also revealed that the vast majority of thermocouple users — including users with high accuracy requirements — have attained few economic benefits in the use of thermocouples calibrated to the current, internationally agreed upon temperature scale compared to thermocouples calibrated to the previous temperature scale. As a result, returns have been poor

on investments made by NIST to upgrade the thermocouple reference tables to be consistent with the newer temperature scale. Yet, NIST made a sound decision by investing in the updated reference tables under the circumstances, and U.S. industry would likely have suffered negative economic consequences if NIST had not made this investment. However, a positive consumer surplus has not been achieved due to a mismatch in the timing of when this infrastructure technology can effectively meet the practical needs of industry (thermocouple users). Thus, the poor return on investments made by NIST for updating thermocouple reference tables is rooted in the decision to change the temperature scale to the ITS-90. Perhaps such investments would have been more effective if better intelligence were available on the timing of the economic payoff for industry including dependency on foreign trade. Hence, the policy implications are that investments in state-of-the-art technology infrastructure should be more rigorously coordinated with the realities of industrial demand and, hence, corporate strategy.

1. INTRODUCTION

1.1 NIST

The United States Department of Commerce (US DoC) through the National Institute of Standards and Technology (NIST) supports U.S. industry's efforts to develop new technologies, accelerate commercialization of new products and processes based on these technologies, and achieve global market penetration to advance the Nation's economic growth and standard of living. The internal laboratory research portion of NIST's activities provides this support in the form of various types of standardization, testing, and laboratory accreditation services that are needed by industry at several critical stages in the process of meeting the challenge of the technological state-of-the-art. NIST is the only Federal laboratory with the primary mission of supporting the commercial application of technology.

NIST's laboratories develop and transfer infrastructure technologies to industry. Infrastructure technologies (infrastructure technologies) are "tools" that make the R&D, production, and market penetration stages of the product cycle more efficient. These tools enable industry to efficiently develop applications that are based on both generic and proprietary technologies.¹

NIST develops a wide range of infrastructure technologies for U.S. firms' products and processes — as well as their attendant products and services — which comprise complex systems. Examples of infrastructure technology tools include production methods, processing models, advanced measurement methods, technical databases, standards, product performance tests, and quality assurance techniques. NIST develops its tools commensurate with the commercialization needs of U.S. industry, which have become ever more demanding to be competitive internationally.

1.2 NIST THERMOCOUPLE CALIBRATION PROGRAM

The NIST Thermocouple Calibration Program (TCP) is a part of the NIST Chemical Science and Technology Laboratory (CSTL). The overall mission of NIST/CSTL is to provide the chemical measurement infrastructure for enhancing U.S. industry's productivity and

¹ The role of infrastructure technology within the construct of product development is discussed in: Gregory Tasse, *The Economics of R&D Policy*, (Quorum Books, 1997; Chapter 8) (forthcoming); and Albert N. Link and Gregory Tasse, *Strategies for Technology-based Competition*, (Lexington Books), pp. 16-21, 1987.

competitiveness, assuring equity in trade, and improving public health, safety and environmental quality. Such measurement technology is required for industrial research and development, product applications, improvements in the design and manufacturing of quality products, proof of performance, and marketplace transactions that include the entry of U.S. products into international markets.

NIST's role as the lead U.S. agency for temperature measurement is to overcome technical and business barriers that require NIST's special characteristics: an impartial position, expertise in a wide range of measurement areas, direct access to complementary national standards, and the motivation to deliver the technical infrastructure to a wide range of supplier and user industries. These characteristics permit NIST to perform functions that individual companies cannot perform:

- Gain access to technical information for resolving industry-wide measurement problems
- Develop measurement solutions and national reference standards that benefit the industry as a whole across diverse product and process lines
- Gain acceptance of those solutions by U.S. industry and its customers so that U.S. products can be sold efficiently both domestically and abroad

All temperature measurements must ultimately trace back to national standards to provide consistency and accuracy across disparate organizations and industries. NIST has the legal mandate in the United States for providing the national standards that form the fundamental basis for all temperature measurements made in domestic industry.² Realizing and maintaining national temperature standards in terms of the scientific first principles and the constants of nature that define the International Temperature Scale is difficult technically and requires a dedicated laboratory capability. NIST/CSTL develops and maintains the scientific competencies and laboratory facilities necessary to preserve and continuously refine the basic physical quantities that constitute the national temperature standard. Further, NIST has the mandate to apply these basic

² Congress passed The Organic Act of 1901 identifying the National Bureau of Standards (NBS) as the responsible organization for providing measurement standards to industry. Subsequent legislation under the Omnibus Trade and Competitiveness Act of 1988 transferred this responsibility from NBS to the renamed NIST.

measurement standards to develop uniform and widespread measurement methods, techniques and data.

1.3 CASE STUDY OBJECTIVES

Periodic economic studies are conducted at NIST to determine the qualitative and quantitative impacts of its programs on U.S. industry. The results of these studies are used for NIST strategic planning and for characterizing NIST's role as a major source of technology infrastructure for U.S. industry.

This case study estimates the first-order economic impacts of the infrastructure technology development on U.S. industry from the calibration of thermocouples. The analysis examines the impacts of the infrastructure technology in terms of the affected industrial activities, the qualitative nature of the impacts on the behavior of relevant industries, and the quantitative impacts on the competitive performance of these industries. The specific objectives established at the onset of the study were to :

- Describe the use of thermocouples in U.S. industry
- Identify and describe the infrastructure technology supporting thermocouple calibrations
- Obtain qualitative and quantitative data on the economic impacts attributable to the contributions from NIST's infrastructure technology; these economic impacts include assessments of the benefits and costs from the perspectives of users, producers, and other organizations that influence and are influenced by temperature measurements made with thermocouples
- Analyze the data and calculate the rate of return on NIST's investments in technical knowledge for thermocouple calibration using various economic measures
- Prepare a report of the findings, analysis and conclusions

1.4 CASE STUDY OUTLINE

The remainder of this report includes the following:

- Chapter 2 provides a technical overview of thermocouples including a generic description of their function and their need for calibration
- Chapter 3 describes thermocouples from an industrial context in terms of:
 - Types of applications
 - Quality and cost drivers for thermocouple accuracy
 - The industrial structure for commercial trade in thermocouples
 - The scheme for standards traceability that allows industrial users to efficiently attain accurate measurement calibrations
- Chapter 4 describes the scope, benefit measures and data collection strategy used for the analysis in this study
- Chapter 5 identifies findings on the qualitative and quantitative economic impacts of the infrastructural outputs from the NIST TCP based on surveys of thermocouple users and suppliers, and lists expenditures and income for the NIST TCP
- Chapter 6 provides quantitative estimates of the prospective economic rate of return from investments made in the NIST TCP, and analyzes certain economic issues that are more qualitative in nature
- Chapter 7 discusses the primary conclusions for this case study

2. TECHNICAL OVERVIEW³

2.1 CIRCUIT

A thermocouple is an electronic sensor for measuring temperature. Thermocouples operate according to the Seebeck Effect, wherein a closed circuit formed by two dissimilar wires (thermoelements) produces an electrical voltage when a temperature difference exists between the contact points (junctions). The electrical potential difference that is produced is called the thermoelectric electromotive force (emf), also known as the voltage output of the thermocouple. The Seebeck Effect occurs due to the difference in the energy distribution of thermally energized electrons in the material compositions of each thermoelement. The fact that thermoelectric emfs vary from metal to metal for the same temperature gradients allows the use of thermocouples for the measurement of temperature.

A simplified measurement system using a thermocouple is shown in Figure 2-1.⁴ The thermocouple consists of two thermoelement wires A and B that are joined at one end H (the “hot” junction), but the wires otherwise are insulated from each other along their lengths. The other ends C_A and C_B (the “cold” junction) are maintained at a constant reference temperature T_0 which usually is defined as the melting point of ice ($0\text{ }^\circ\text{C}$). In practical measurements, the cold junction does not have to be held at the reference temperature if the actual temperature is known. The difference between the actual temperature and $0\text{ }^\circ\text{C}$ is usually corrected electronically in the instrumentation of the measuring system. This adjustment is referred to as the cold-junction (CJ) compensation.

³ This chapter is based primarily on the following: G.W. Burns and M.G. Scroger, *The Calibration of Thermocouples and Thermocouple Materials*, NIST Special Publication 250-35, April 1989; H. Dean Baker, et al., *Temperature Measurement in Engineering*, (Omega Engineering: 1975); G. W. Burns, et al., *Temperature-Electromotive Force Reference Functions and Tables for the Letter-Designated Thermocouple Types Based on the ITS-90*, NIST Monograph 175, April 1993; *The Temperature Handbook*, (Omega Engineering: 1995); and, D.D. Pollack, *The Theory and Properties of Thermocouple Elements*, ASTM STP 492, 1971.

⁴ The scale of the conceptual measurement system represented in the figure varies widely depending on the application. In reality, the overall distance from T_l to T_r may range from 2 feet to 2,000 feet.

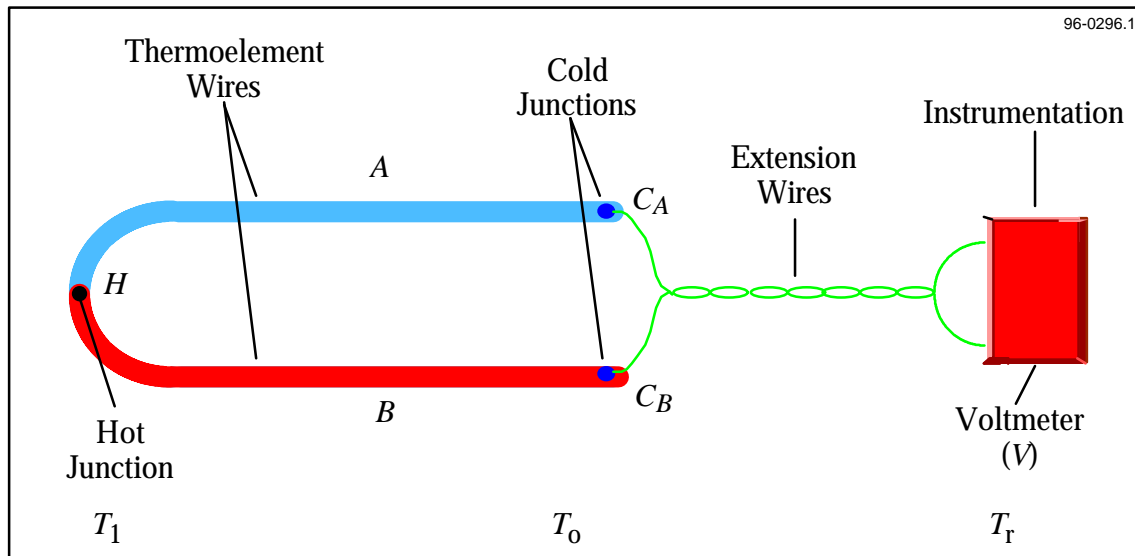


Figure 2-1 Basic Circuit for Thermocouple Thermometry

A thermoelectric emf (voltage) is generated between junctions C_A and C_B when the hot junction is exposed to the temperature of interest T_1 and the cold junctions are maintained at the reference temperature T_0 . Identical wires extending from the cold junctions of the thermocouple transmit the emf to an instrument — represented in the figure by a voltmeter at room temperature T_r — that measures the thermocouple emf. Theoretically, this measurement depends only on the temperature difference $(T_1 - T_0)$.⁵ As T_1 increases, the output emf of the thermocouple increases, although not necessarily in a linear relationship. This correlation of temperature versus emf permits the establishment of mathematical relationships that are unique to various wire combinations. These mathematical relationships are expressed in reference functions and tables which provide the basis for calibrations used in thermocouple thermometry.

2.2 TYPES

About 300 combinations of pure metals and alloys have been identified and studied as thermocouples. Such a broad selection of different conductors is needed for applications requiring certain temperature ranges as well as for protection against various forms of chemical

⁵ If, however, the wires A and B are not homogeneous, then the thermoelectric emf may not be correct. Herein lies the principal limitation in the use of thermocouples for accurate temperature measurement. In practice, obtaining perfectly homogeneous wires has been impossible. Moreover, the degree of starting homogeneity is degraded to some extent after the wire materials are first heated.

contamination and mechanical damage. Yet, only a few types having the most desirable characteristics are in general use.

The eight most common thermocouple types used in industry are identified by letters: base-metal types E, J, K, N, and T; and noble-metal types B, R, and S. The letter designations were originally introduced by the Instrument Society of America (ISA) to identify certain common types without using proprietary trade names, and were adopted in 1964 as American National Standards. The letter-types are often associated with certain material compositions of the thermocouple wires. However, the letter-types actually identify standard reference tables that can be applied to any thermocouple having an emf versus temperature relationship agreeing within the tolerances specified in the table, irrespective of the composition of the thermocouple materials. The letter-type thermocouples comprise about 99 percent of the total number of thermocouples bought and sold in commerce.

Thermocouples made from the noble-metal materials (mainly, platinum and rhodium) are significantly more expensive than those made from base-metal materials (e.g., copper, iron, and constantan). For example, prices for 0.015 inch diameter bare wires made of various platinum-rhodium alloys range from \$25 to \$101 per foot while the price range of similar base-metal wire is \$0.20 to \$0.24 per foot.⁶ This significant difference in cost is the primary reason why over 90 percent of the total number of thermocouples sold are base-metal type. In the United States, several hundred tons of base-metal thermocouple wire are produced annually.

2.3 CALIBRATION

Thermocouples must be calibrated for accurate temperature determination. In most cases, calibration involves measuring the thermoelectric emf of the thermocouple under evaluation as a function of temperature, which is determined by a reference thermocouple.

The calibration process consists generally of three steps. First, thermoelectric emf values of the thermocouple are measured either at a series of approximately uniform intervals of temperature or at certain fixed points. Second, appropriate mathematical methods are used to fit the difference between the measured emf values and those of a reference temperature. Third, the

⁶ Based on a range of catalog prices for thermocouple wire as quoted in *The Temperature Measurement Handbook*, Vol. 29, Omega Engineering, Inc.

emfs as a function of temperature are expressed in both a calibration table and their given mathematical relationship.

The reference functions and tables used in calibrations of standard letter-type thermocouples must relate to a specified temperature scale. International agreements have been in place since 1927 on scales of temperature for scientific and industrial purposes. Updated about once every 20 years, the scale now in use is the International Temperature Scale of 1990 (ITS-90).⁷

The extent of thermocouple calibration for practical temperature measurement depends mainly on the accuracy and stability required for the particular application.⁸ Wire suppliers typically perform sample calibrations on short wire lengths from spools containing up to 1000 feet of wire. Sample calibrations of base-metal wire provide tolerances ranging commonly from +/- 0.25 percent to +/- 0.75 percent of the temperature versus emf values in the standard reference tables, which provides sufficient accuracy for a wide variety of technical work.⁹ However, uncertainties in process control and the need for more accurate measurements demand additional calibrations by certain suppliers and users of thermocouples. For example, the stringent accuracy and stability demands for temperature measurements made in semiconductor manufacturing processes often require calibration of every thermocouple.

Significant differences in stability and accuracy exist between the noble-metal and the base-metal types of thermocouples. Noble-metal type thermocouples tend to have fairly stable calibrations and tight calibration tolerances. On the other hand, the base-metal types are less stable

⁷ The International Temperature Scale of 1990 (ITS-90) was adopted during the 1989 meeting of the International Committee of Weights and Measures in accordance with the request embodied in Resolution 7 of the 18th General Conference of Weights and Measures of 1987. This scale supersedes the amended edition (1975) of the International Practical Temperature Scale of 1968 (IPTS-68) and the 1976 Provisional 0.5 K to 30 K Temperature Scale.

Temperature values on the ITS-90 (expressed as t_{90}) are defined in terms of thermodynamic equilibrium states of pure substances (the defining fixed points), thermometers for interpolating between the fixed points, and equations that relate the measured property to t_{90} .

⁸ Stability refers to the ability of a thermocouple to achieve repeatable temperature versus emf characteristics with successive temperature measurements. An unstable thermocouple can go out of calibration or “drift”, which is a serious fault because of the resulting incorrect reading of temperature.

⁹ Certain suppliers of noble-metal wire claim to provide even tighter tolerances, ranging from +/- 0.1 to +/- 0.33 percent.

(more likely to go out of calibration with frequent use) and have larger tolerances.¹⁰ Therefore, the more stringent the stability and accuracy requirements of the particular application, the more likely that users pay the higher costs for noble-metal thermocouples.

¹⁰ Material composition of the wires is the driver for stability. Increases in temperature creates greater molecular movement in alloyed metals than with pure materials. As a result, noble-metal wire is more stable due to the greater purity in material composition in comparison to the metal alloys used in base-metal wire.

3. INDUSTRIAL OVERVIEW

3.1 APPLICATIONS

The thermocouple is the oldest and the most widely used electronic temperature sensing device. Other devices, such as thermistors, resistance temperature detectors, and integrated circuit sensors, can be substituted for thermocouples, but only over a limited temperature range. Therein lies the primary advantage of thermocouples, which is their use in a wide temperature range (-270 C to 2100 C). Other key advantages are that they provide a fast response and are unaffected by vibration. They also are self-powered, versatile, inexpensive, and simple in their construction. Their calibration, however, is affected by material inhomogeneity (nonuniformity of physical composition) and contamination, and their operation is susceptible to electrical interference.

Thermocouples are used in a wide variety of applications (e.g., medical procedures, scientific research, automated manufacturing processes, and consumer products) where temperature is an important parameter in a measurement or control system. Their use in engineering applications has been increasing steadily because thermocouples, like other types of electronic measurement sensors, are compatible with microprocessor instrumentation.¹¹ Figure 3-1 shows typical levels of uncertainty for a variety of products and manufacturing processes that use thermocouples for temperature measurement.¹² Applications having the more stringent requirements of uncertainty have greater needs for calibration knowledge than those applications having the less stringent requirements.

¹¹ A temperature measure in the form of a digital output is useful in computer-based engineering applications. An electronic temperature sensor generates an electrical output in direct response to a change in temperature, and this electrical output is adaptable to a microprocessor. By contrast, a traditional dial thermometer produces a non-electrical output, which requires a gauge reading by an operator to obtain the measurement.

The industrial demand for electronic temperature sensors is significant and expanding as the monitoring function of various control systems becomes more computerized to improve productivity and quality as well as to reduce operator error. Intechno Consulting AG reported that the world temperature sensing market had sales of \$2.5 billion in 1991 and was forecast to increase at a 6.4 percent average annual rate to reach \$4.7 billion in 2001.

¹² NIST uses the term “uncertainty” as the quantitative measure of inaccuracy.

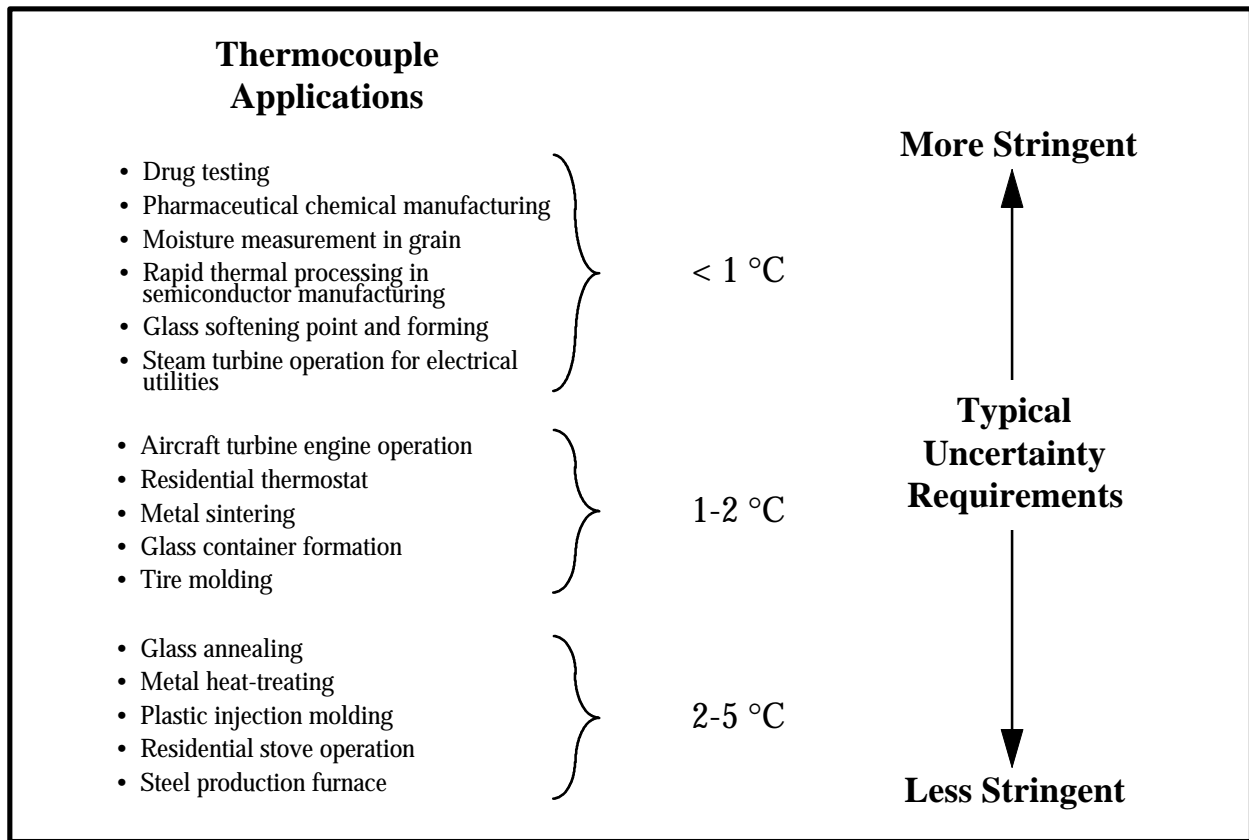


Figure 3-1 Sample Applications of Thermocouples by Common Requirements of Uncertainty

Certain industries have applications that are very sensitive to temperature change. According to various industry representatives, the four industries having the most stringent accuracy and stability requirements for temperature measurement are:

- Food, beverage and drug
- Semiconductor manufacturing
- Military/aerospace
- Power utilities

For example, small temperature measurement inaccuracies in burning fuel for generating electrical power can translate into large inefficiencies and hence costs. A utility industry representative stated that an inaccuracy of 1 °C would result in an annual \$100,000 loss in pre-tax profits for a single fossil-fired power generation plant. Also, IBM reports that a 3 °C miscalculation in a

sintering process can jeopardize a furnace load of substrates worth perhaps millions of dollars.¹³ Additionally, a supplier of gas turbine engines used in aircraft stated that if the on-board temperature measurements of thermocouples used in the turbine are inaccurate by 1 °C, then the aircraft would burn two percent more fuel. Therefore, such thermocouple users with high accuracy requirements have greater economic sensitivity than the majority of users.

3.2 COST AND QUALITY DRIVERS FOR ACCURACY

According to thermocouple experts, the key factors in obtaining accurate measurements in thermocouple thermometry are:

- Quality of the components in the temperature measurement system
- Minimizing contamination in thermocouple wires¹⁴
- Quality of calibration data that is traceable through standards at NIST

In addition to absolute accuracy, the precision of a temperature measurement in a fixed environment (e.g., a furnace) that requires periodic replacement of thermocouples is also critical in maintaining process control. Therefore, consistent performance in the interchangeability of thermocouples is an important feature for achieving high production yields and reducing costs.

An example in glass forming helps in understanding the combination of several key concepts: the use of temperature measurement to ascertain product quality, the need for stringent levels of accuracy in temperature measurement, and consistent performance required in the interchangeability of thermocouples. Viscosity of molten glass is the key technical parameter in forming picture tubes used in television sets. Levels of viscosity are inferred through temperature measurements made with thermocouples because viscosity cannot be measured directly. Measuring the absolute accuracy of the glass softening point to within 1 °C is important in obtaining the desired mechanical properties of the glass. Also, uniform levels of viscosity — via repeatable temperature measurements with interchangeable thermocouples — are important in ensuring consistent quality in manufacturing the glass picture tubes.

¹³ “Temperature Control is the Key in IBM’s Sintering Process,” *Intech*, May 1997.

¹⁴ For example, contamination in the wires of a thermocouple due to human perspiration and fingerprints is a major source of measurement error in many applications requiring high temperature accuracy. For this reason, many thermocouples are manufactured in clean room environments.

Generally, the number of calibrations and the quality of calibrations generally have been steadily increasing industry-wide.¹⁵ The major reason for this trend is the increased number of organizations seeking higher levels of quality in their products and processes. In particular, the need for traceability to standards, which is one key requirement for achieving certification and audit approval in the ISO 9000 quality scheme, has been a driving force for increases in the quantity and quality of thermocouple calibrations. The industrial literature also cites the increased need for tighter measurement tolerances and quality in applications involving health, safety, hygiene, and process control.

Large differences in sell price between thermocouples made from base-metals and noble-metals often strongly influence users' willingness to pay for calibration testing. Most base-metal types of thermocouples and thermocouple assemblies retail in the range of \$6 to \$100 per unit.¹⁶ On the other hand, prices of noble-metal thermocouples range from \$250 to \$1,000 per unit. Using estimates from commercial calibration service providers, the cost of performing a calibration test for most types of thermocouples ranges from about \$40 to \$100. Therefore, the percentage of total unit price attributable to calibration is much greater for base-metal thermocouple types than for noble-metal types. This is the primary reason that some users of base-metal thermocouples only perform sample calibrations from large lots. For example, one representative of a thermocouple manufacturing company stated that few calibrations are performed on thermocouples sold to the plastic injection molding industry because base-metal thermocouples are used and temperature sensing requirements are not very stringent; these industrial users rely on the sample calibration data provided by the wire supplier, which is sufficient for most plastic injection molding applications. On the other hand, some industrial users in the four critical industries noted above require calibration of every base-metal thermocouple. Obviously, the percentage of sell price attributable to calibration testing will be higher for this latter class of users.

¹⁵ Estimating the annual number of calibrations performed by thermocouple users and producers is impractical due to variations in quality requirements across industries and firms.

¹⁶ Based on a range of catalog prices for thermocouples quoted in *The Temperature Measurement Handbook*, Vol. 29, Omega Engineering, Inc.

3.3 INDUSTRIAL STRUCTURE

3.3.1 Suppliers

The thermocouple industry consists of wire suppliers and thermocouple suppliers. The downstream customers of the wire suppliers are grouped into two general categories, thermocouple suppliers and thermocouple users that fabricate and assemble thermocouples captively. As mentioned earlier, the wire suppliers typically perform sample calibrations on each production lot of wire. Depending on the accuracy requirements of a given application, these sample calibrations may or may not be sufficient for users of the thermocouple. Therefore, the supplier or user/producer may perform additional calibrations as necessary. According to NIST, the three major suppliers of base-metal type wire are Carpenter Technology, Harrison Alloys, and Hoskins Manufacturing. The four main suppliers of noble-metal wire are Engelhard Industries, Johnson Matthey, PGP Industries, and Sigmund Cohn Corporation.

Thermocouple suppliers purchase wire from the wire suppliers to fabricate and assemble finished thermocouple products. Steps in fabricating such products include encasing a thermocouple in protective sheathing and adding ancillary hardware such as a connector. Myriad configurations of assembled thermocouples are sold, in turn, to users of thermocouples. The on-line product database of the Thomas Register of American Suppliers lists 305 companies selling thermocouple products.¹⁷

3.3.2 Users

The available information on characteristics of the domestic thermocouple market is less than complete and current. Also, disparities exist among the few sources of market data that are available.¹⁸ The best available information is in several industry trade periodicals and newsletters (*Sensor Business Digest*, *Measurement and Control News*, and *Sensor Business News*) that cover activities in the thermocouple industry. Past articles refer to results from a 1992 study on the temperature sensor industry performed by Venture Development Corporation (Natick, MA)

¹⁷ Thomas Register of American Suppliers, <http://www.thomasregister.com>, September 28, 1996. Many industry representatives consider the Thomas Register to be the most complete and reliable listing of thermocouple suppliers. However, most of the firms listed in the Thomas Register are small, specialized producers or repackagers of other firms' products.

¹⁸ Such disparities in data among different market research firms are common.

which includes information on the thermocouple segment of the industry.¹⁹ The following market data and forecasts were reported from this study:

- The total domestic shipments of all electronic temperature measurement devices (thermocouples, RTDs, thermistors, and IC sensors) was \$402 million in 1991
- US consumption of thermocouples was projected to increase at a compound annual rate of 2.6 percent from \$126 million in 1991 to \$144 million in 1996
- Consumption of temperature sensing devices is significant in the following industries:
 - Automotive
 - Chemical
 - Consumer Goods
 - Food/Beverage/Pharmaceutical
 - Glass
 - HVAC (heating, ventilating, and air conditioning)
 - Medical
 - Metals
 - Military/Aerospace
 - Oil/Petrochemical
 - Plastics/Rubber
 - Utilities
- The medical, HVAC and automotive categories were forecast to have the highest growth rates domestically for temperature sensors

A 1991 report by a German firm, Intechno Consulting AG, on the world temperature sensors market stated that the world temperature sensing market had sales of \$2.5 billion in 1991 and was forecast to increase at a 6.4 percent average annual rate to reach \$4.7 billion in 2001. The geographical distribution of this market is U.S. (33.4%); Japan (23.7%); and Europe (42.7%). Regarding thermocouples, Intechno estimated that the 1991 world market was \$1.032

¹⁹ For example, see “Dartmouth Researchers Invent Improved Temperature Sensor Array,” *Sensor Business Digest*, March 1994.

billion, consisting of \$263.5 million in non-encased thermocouples and \$768.6 million in encased thermocouples.²⁰

Thermocouples and thermistors are widely used in the health care industry, particularly for monitoring the core body temperatures of patients in many situations, such as anesthetized surgery, outpatient surgery, trauma centers, intensive care, and in pain clinics. Market Intelligence, Inc. projected in 1991 that the worldwide biomedical sensor market for disposable thermocouples and thermistors would grow from \$63.2 million in 1991 to \$115.6 million in 1998 for a 9 percent compound annual rate during the forecast period.²¹ Actual unit shipments were estimated at 11.1 million in 1991 and projected to increase to 22.5 million in 1998. The U.S. market consumed 58.1 percent of the world revenues in 1991.

3.3.3 Infrastructure

NIST Thermometry Group NIST/CSTL's Thermometry Group develops and applies the process of standards traceability for temperature measurement. The Thermocouple Calibration Program (TCP) is a part of the Thermometry Group's overall research activities. This Group is responsible for realizing, maintaining, improving and disseminating the national standards of temperature. This responsibility is implemented through the following activities:²²

- Determining the accuracy of the national standards of temperature with respect to fundamental thermodynamic relations
- Calibrating practical standards for the U.S. scientific and technical communities in terms of the primary standards
- Developing methods and devices to assist user groups in the assessment and enhancement of the accuracy of their temperature measurements
- Preparing and promulgating evaluations and descriptions of temperature measurement processes

²⁰ Ibid.

²¹ "Tayco's Temperature Sensors Solve Challenging Applications," *Sensor Business Digest*, July 1993.

²² National Institute of Standards and Technology, "Thermometry Group Mission," <http://www.cstl.nist.gov>, October 31, 1996.

- Coordinating temperature standards and measurement methods nationally and internationally
- Conducting research towards the development of new concepts for standards
- Developing standard reference materials for use in precision thermometry

The above listing shows that NIST does more than simply maintain national standards to ensure that industry has a traceable temperature measurement system. NIST also develops and makes available suitable, appropriate, and meaningful measurement methods that permit organizations to correctly use internal instrumentation and reference standards to perform their needed measurements at the required accuracy.

Standards Bodies Several national and international organizations sanction standards for practical temperature measurement. These standards often form the basis of purchase specifications used in commercial trade between users and suppliers of thermocouples. ASTM and the ISA are the primary industrial organizations that sanction thermocouple standards used domestically, and different technical specifications are covered in the standards documents of each organization.²³ The ISA Standard MC-96.1 has been recognized as an American National Standard, while the related ASTM Standard E-230, which has been updated to include ITS-90 thermocouple tables and functions, is presently under consideration as an American National Standard by ANSI.²⁴ IEC 584-1 is the standard used internationally.²⁵

The thermocouple standards from ASTM, ISA, and IEC subsume calibration reference tables from NIST. The current versions of ASTM E-230 and IEC 584-1 have been updated to include NIST's most recent reference tables and functions, while the current ISA MC-96.1 standard — the latest update was in 1982 — contains an earlier version of NIST's reference tables.²⁶ Therefore, in practice, the benefits of NIST's reference tables are diffused to

²³ ASTM is the American Society for Testing and Materials, and ISA is the Instrument Society of America.

²⁴ ANSI is the American National Standards Institute.

²⁵ The IEC is the International Electrotechnical Commission.

²⁶ According to several industry representatives, this discrepancy between the ISA and the ASTM standards has often caused confusion and disputes in domestic thermocouple commerce.

thermocouple users and producers through the ASTM, ISA, and IEC standards rather than through NIST-published documents such as Monograph 175.

The ASTM, ISA, and the IEC standards also include other technical specifications, such as color-coding of the thermoelement wires and the extension wires, that are needed in the course of commercial trade between users and suppliers of thermocouple products. NIST contributes little technical work or engineering data for developing these more mundane types of specifications since they are not based on leading-edge measurement technology.

NIST also cooperates with standards laboratories of other countries to ensure full compatibility on basic measurement standards used in international trade. While the standards bodies governing various countries agree on both the International Temperature Scale and NIST's reference functions and tables for thermocouple calibration, disagreements often occur on allowable tolerances relative to these reference tables. Tolerances of the United States are specified in the ISA and ASTM standards. Developing international consensus on thermometer tolerances is one part of the charters of the IEC and the Organization of Legal Metrology (OIML), and NIST participates actively in both of these international organizations.

Commercial Calibration Services Companies that market commercial calibration services comprise another facet of the thermocouple industrial infrastructure. The objectivity of a neutral third party is often valued in negotiations or disputes between suppliers and purchasers of thermocouples, and the requirement of traceability can avoid potential disagreements or misinterpretations of data. The strength of competitive factors such as pricing, quality, and turn-around time generally determine whether thermocouple users and producers seeking third-party calibration testing use these secondary-level calibration service providers rather than the primary-level services of NIST. Industry representatives concur that NIST provides the highest level of standards traceability for achieving the highest quality calibrations. Yet many are sensitive to the price of calibration services and perceive the cost of NIST's services as relatively high for their specific needs. However, one of NIST's major strategic thrusts is to have its primary standards leverage the private sector provision of secondary standards.

3.4 TRACEABILITY OF STANDARDS

In the overall hierarchy of standards for thermocouple calibration, NIST is viewed as the provider of primary standards from which subordinate reference standards are traced.²⁷ The general traceability paths for thermocouple users, suppliers, and calibration service providers are depicted in Figure 3-2. For example, a user needs a thermocouple calibrated to a certain specification for assurance of accurate results. In the traceability scheme, the user often relies on the proficiency and cost-effectiveness of suppliers or a calibration laboratory in the private sector to obtain this calibration. To certify the accuracy of the relationship between temperature and thermoelectric emf for the thermocouple, the supplier must have direct access to appropriate reference standards calibrated in terms of the primary temperature standards maintained at NIST. The producer or commercial laboratory maintains these reference standards internally and compares them regularly with the national standards to achieve traceability.

²⁷ In the context of measurement science, the system of providing a thoroughly documented, “unbroken chain” of references to a measurement authority is known as traceability. Many motivations exist for this system in industrial commerce, ranging from the need for compliance with stated contractual requirements to the desire for using the best possible practices in measurement. Traceability also provides an efficient means for ensuring accurate measurements in industrial environments.

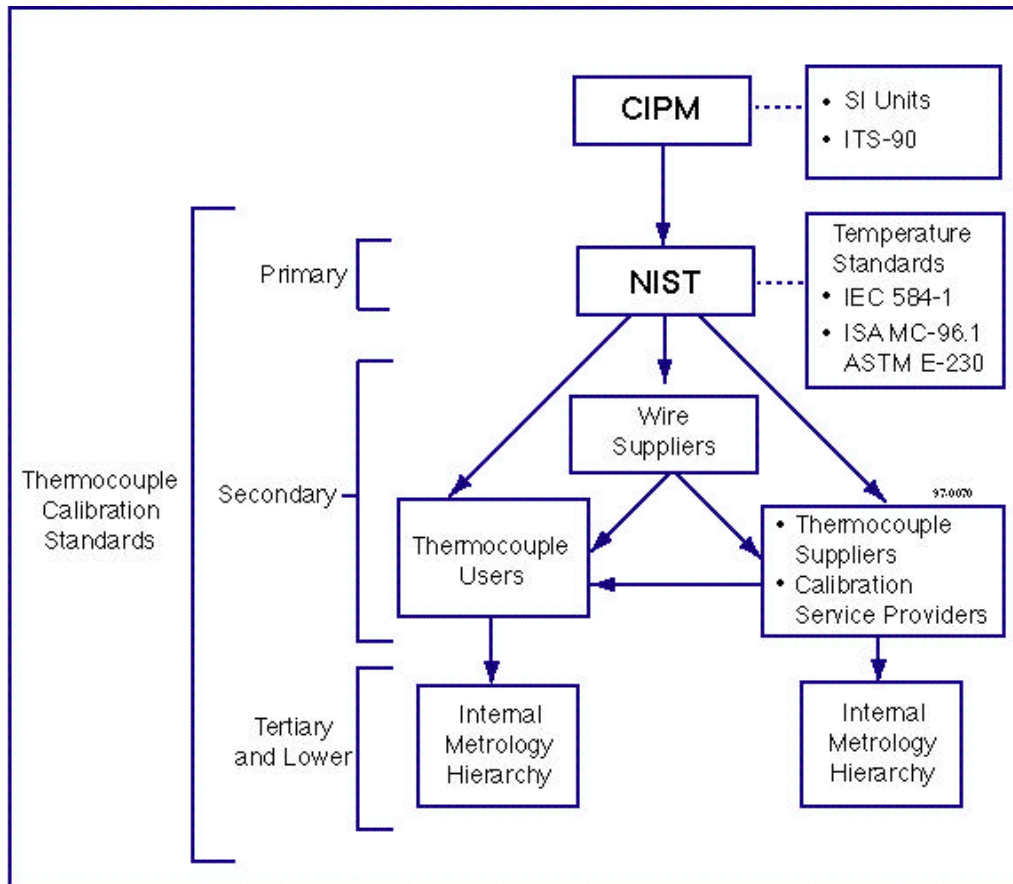


Figure 3-2 Traceability Paths for Thermocouple Calibration Standards

Organizations that perform internal calibrations of thermocouples employ several general methods to demonstrate and certify traceability to NIST’s national temperature standards. Sometimes a temperature measurement is rendered traceable via more than one of these methods. In the first and most common method, the organization has its thermocouple materials calibrated against the national (primary) standards maintained at NIST. These materials then serve as the reference standards (artifacts) for internal calibration purposes of the organization. The second established but less common method involves measurement and certification using test methods and similar quality apparatus employed by NIST. The third and most recent method for thermocouple calibration involves the organization’s acquisition of a standard reference material (SRM) from NIST. The SRM is then used as the artifact for internal calibration purposes.

An approach known as the “expendable standard” is typically employed by the wire suppliers to perform internal reference calibrations efficiently. Periodically (about every 1-5 years), a sample length of wire from a large wire spool is calibrated through the primary

calibration services at NIST. This NIST-calibrated wire sample becomes the reference standard (the traceable link to NIST's primary standards) for the organization. Short wire lengths of the spool from which this reference standard originated are used for subsequent internal calibration tests. These test lengths, which are traceable to the NIST primary standards via the reference standard, are the expendable standards since they are used typically for only one calibration test and then discarded.

Users of thermocouples employ one or a combination of strategies in the procurement and calibration of thermocouples depending on their operating practices and accuracy requirements. As mentioned in Section 3.3.1, users obtain thermocouples by either: (1) purchasing assembled thermocouples from suppliers, or (2) maintaining captive production operations by procuring wire from wire suppliers directly and making thermocouples for internal use. Users in the first group usually rely completely on calibration data provided by the thermocouple suppliers to ensure specified levels of quality. One representative of a thermocouple supplier stated that 95 percent of his customers rely exclusively on the supplier's calibration data to ensure thermocouple accuracy. Also, these types of users sometimes send used thermocouples back to the OEM for recalibration, although disagreement exists among thermocouple experts on the ability to effectively recalibrate a used thermocouple.

Thermocouple users often perform their own calibrations in-house to attain certain levels of accuracy beyond the calibration warranties provided by their suppliers. These internal calibrations are performed either in the user's metrology laboratory or in situ (in the internal operating environment of the thermocouple).

4. EVALUATION FRAMEWORK AND APPROACH

4.1 SCOPE

This section describes the outputs of the NIST Thermocouple Calibration Program under assessment in this case study.

4.1.1 Reference Functions and Tables

NIST has a long history of developing and publishing reference functions and tables for letter-type thermocouples. NIST has updated this reference data with the periodic changes in the International Temperature Scale. The most current reference functions and tables for the eight standard letter-type thermocouples have been published in NIST Monograph 175.²⁸ This reference data is derived from actual thermoelements that conform to the requirements of the ITS-90 standard.

As described in Section 3.3.3, NIST's reference functions and tables have been subsumed in the major industry standards for thermocouple calibration. Therefore, this infratechnology is used every time a letter-type thermocouple is calibrated, providing significant and widespread benefits to thermocouple users and suppliers.

4.1.2 Primary Calibration Services

NIST's Thermometry Group provides primary calibration services for the suppliers and users of thermocouples to achieve levels of measurement accuracy necessary to attain objectives of quality, productivity, and competitiveness. These services constitute the highest order of thermocouple calibration available in the U.S. for customers seeking traceability and conformity to national and international temperature standards. NIST provides these services at a charge sufficient to compensate for the direct costs of the calibration, and certain surcharges apply to help pay for fixed costs and research.

All types of thermocouples, including both letter-designated and non-standard types, can be calibrated by NIST from -196 °C to 2,100 °C. Customers provide samples (either bare wires or

²⁸ G. W. Burns, et al., NIST Monograph 175, April 1993.

complete thermocouples) to NIST’s laboratory. NIST calibrates these samples on the ITS-90 using one or a combination of different test methods depending on the thermocouple type, the temperature range, and the required accuracy. The calibrated thermocouple is then shipped back to the customer along with a “NIST Report of Calibration” containing the test procedures and the results of the calibration. The sample and the data from the NIST Report constitute the traceable link to national temperature standards. For example, customers of NIST’s primary calibration services can use their calibrated artifact and the accompanying calibration data from the NIST Report of Calibration as the secondary standard for internal quality control purposes. This secondary reference standard links subsequent calibrations made within the customer’s metrology regime to the primary standards maintained by NIST, and, thereby, to the measurements of other organizations. Such traceability to standards allows the highest level of fidelity for the organization’s internal calibrations.

The technical knowledge that forms the foundation for NIST’s calibration services is upgraded continuously to improve the traceability process.²⁹ These improvements are generally in the forms of research on test methods and procedures as well as upgraded equipment, instrumentation, and facilities.

4.1.3 Technical Support to Industry

Experts at NIST are available regularly to assist in solving specific technical problems of industrial organizations. Such problems usually pertain to performing thermocouple calibrations or using thermocouples in a temperature measuring system. Direct help is available over the telephone — NIST estimates that each of its staff members receives about 20 to 25 telephone calls per week — and by visits to the Thermometry Group’s laboratory at Gaithersburg, MD.

NIST’s specialized expertise in calibration test methods and procedures is particularly sought by industry. Organizations with internal metrology laboratories often seek technical know-how from NIST in establishing and maintaining sound test methods for thermocouple calibrations. These organizations benefit from the research invested by NIST to establish the primary

²⁹ Detailed technical descriptions about NIST’s thermocouple calibration services are published in *NIST Special Publication 250* and its supplements. These documents augment the “NIST Report of Calibration” and encompass the following topical areas: specifications for the service, design philosophy and theory, description of the NIST measurement system, NIST operational procedures, assessment of measurement uncertainty, and NIST internal quality control procedures.

calibration services discussed above. To achieve high levels of traceability internally, some organizations perform secondary-level calibrations by replicating test techniques and similar apparatus used at NIST.

Periodically, NIST gives tutorials on thermocouple calibration at conferences and seminars. These tutorials provide education and promote good measurement practices at all levels throughout industry. NIST also provides advice and assistance on problems in thermocouple measurement and calibration as a part of a precision thermometry workshop held twice a year in the NIST laboratories at Gaithersburg, MD. Additionally, technical papers regarding NIST research in the measurement field are disseminated at conferences organized by various scientific and engineering groups.

4.2 BENEFIT MEASURES

Based on background interviews with NIST and several thermocouple users and suppliers, the working hypothesis for the case study was that the infrastructural outputs attributable to the NIST TCP provide users and suppliers with three main types of benefits:

- (1) *Efficiency in developing the infrastructure technology necessary for calibrating thermocouples.* Industry has relied on NIST as the single organization for the outputs described in Section 4.1, above. This reliance has obviated the need for duplicative research by individual companies and industrial consortia.
- (2) *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 (1) high quality outputs, and (2) impartial competitive posture.
- (3) *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 traceability from NIST.

4.3 COMPARISON SCENARIOS

The approach for evaluating the economic benefits associated with the NIST TCP has been adopted from evaluations of other public investments in infratechnology.³⁰ NIST's actual costs are compared to an estimate of net benefits using a hypothetical, counterfactual experiment. The experiment assumes that the first-level economic benefits associated with the NIST TCP can be approximated in terms of the additional costs that industry would incur in the absence of NIST's services. In other words, these are the costs avoided by industry due to the existence of the NIST TCP.

The counterfactual experiment is used because this case study lacks a comparable business baseline prior to the development of NIST's infratechnology outputs. NIST, through its legal mission, has been the sole provider of these infratechnology outputs to U.S. industry for many years. With respect to the reference tables, no substitute or near-substitute set of outputs exists. Conflicting proprietary tables were in use from the 1920s through the 1940s, but that situation no longer exists as industry has relied on NIST for reference tables for letter-designated thermocouples. Therefore, a recent "pre-NIST" baseline for reference tables is not available to compare the behaviors of industry in the "post-NIST" scenario.

For primary calibration services, a similar situation exists because NIST has operated since at least the 1960s — based on the recollections of NIST TCP personnel — as the provider of such services for domestic users seeking high quality calibrations. The commercial calibration services mentioned in Section 3.3.3 are not a comparable substitute since these commercial organizations rely on the laboratory capabilities of NIST for primary measurement standards.

Without an actual state-of-practice from an earlier period, a significant part of the economic analysis framework is based on the hypothetical scenario of how industry would respond if NIST ceased to provide its thermocouple infratechnology outputs. Postulating such a counterfactual scenario was deemed the most feasible approach for analyzing a significant part of NIST's economic impact for this case study, although having a realistic baseline to draw from would have been preferable.

³⁰ See Albert Link, *Evaluating Public Sector Research and Development*, (Praeger: New York, 1996); and Gregory Tasse, *Rates of Return from Investments in Technology Infrastructure*, NIST Planning Report 96-3, June 1996.

4.4 BENEFIT DATA

Two surveys have been conducted for gathering information to determine the economic benefits associated with NIST-supported infratechnologies for thermocouple calibration. In both cases, telephone interviews were deemed preferable to mailed surveys. This decision has been based on previous case study experience which shows that certain economic concepts (e.g., transaction cost savings) are conveyed most effectively in a semi-structured, interactive phone conference.

4.4.1 Survey of Thermocouple Users

A brief survey was conducted from the perspective of thermocouple users to obtain anecdotal evidence of the economic impact from the NIST TCP. Users derive considerable economic benefits from the NIST TCP since accurate temperature measurements from thermocouples are important in achieving downstream product quality and process efficiency. Yet, these benefits have not been quantified across all domestic industrial users for two reasons. First, the economic effect of NIST's infrastructure technology is more direct and quantifiable on the wire suppliers and thermocouple suppliers, and more indirect and difficult to quantify for the users. Based on the pre-survey results, users can identify the general engineering and business reasons for employing accurate thermocouples, but they have difficulty in disentangling the economic benefits attributable to more accurate and frequent calibrations from other factors affecting product performance and process efficiency.

Second, extrapolating the benefits from a representative sampling of user respondents to the large and diverse population of thermocouple users was not feasible within the budgeted resources of the study. The difficulty is due to the greater scope and complexity in the conceptual framework for quantifying net product/process improvements among the diverse industrial user segments in comparison to the more straight-forward framework for quantifying efficiencies for conducting research for the infrastructural outputs and reducing transaction costs.³¹ Therefore, the linkage between the economic benefits of users' products/processes and the NIST TCP is more difficult to discern, much less to quantify. Thus, while the collective economic benefits to

³¹ An alternative approach of quantifying the economic impact on one or a few individual industries (or industry segments) that use thermocouples was considered, but this approach proved to be too difficult because of problems in identifying the population of users within a given industry and the scarcity of appropriate market data.

“second tier” industries are likely substantial, the data collection effort focused on the “first tier” industry, suppliers of wire and thermocouples.

4.4.2 Survey of Thermocouple Industry

A survey of the thermocouple industry was determined to be the feasible focus for gathering data associated with the primary benefits in the hypothetical experiment. The prospective benefit data, which are presented in Section 5.2 and used in the calculation of economic impact measures in Chapter 6, are based on telephone interviews of seven major domestic wire suppliers and twelve major thermocouple suppliers. Based on aggregate levels of domestic market share, these samples effectively represent the entire domestic thermocouple industry.

Consideration was given to conducting a retrospective analysis of net benefits for the hypothetical experiment. However, from a data collection standpoint, experience in previous case studies shows that scientists and engineers are better able to forecast events than to create hypothetical situations retrospectively.

5. SURVEY RESULTS

5.1 THERMOCOUPLE USERS

A telephone survey of 10 thermocouple users has been conducted to attain qualitative insights on their calibration practices and their perception of the value received from the NIST TCP.³² This survey of thermocouple users preceded the survey of the thermocouple suppliers (discussed in Section 5.2) to enhance the quality of the latter survey. Data obtained in the users' survey has not been incorporated in calculations of evaluation measures which are presented in Chapter 6. The remainder of this section provides observations from the results of this survey.

5.1.1 Calibrations Performed Internally

Many users rely on assurances of thermocouple accuracy from calibration tests performed internally rather than from statements of accuracy from their suppliers. This reliance on internal calibrations is not due to concerns about the process of standards traceability via the NIST TCP. Users have confidence in both NIST measurement and standards capabilities and in the ability of suppliers to calibrate thermocouples that are traceable to national temperature standards. Instead, three general factors regarding the stated accuracy of calibration data from suppliers cause concern. The first factor regards practical aspects of calibrations for thermocouple wire and assembled thermocouples in user applications. The emf versus temperature relationship of two

³² The respondents in the survey of 10 thermocouple users include representatives from the utility, military/aerospace, food and beverage, aluminum, and commercial electronics industries. Thermocouple users in these industries having applications with high accuracy requirements ($\pm 1-2^{\circ}\text{C}$) were determined to be best informed about the impact of thermocouple calibration practices on downstream products and/or processes. Such sophisticated users have the most at stake by relying on NIST for standards traceability to obtain accurate temperature measurements. Upon request, a listing of industry representatives of this type was provided by NIST TCP personnel based on their previous professional contacts.

The functional disciplines of the respondents include operational users of thermocouples in production and development environments as well as test engineers in central corporate laboratories who provide working-level calibration standards of thermocouples to operational users employing thermocouples in a wide range of product and process technologies across their organizations. Most of the respondents had general knowledge in all business and technical aspects of thermocouples used in their organizations. All of the respondents use thermocouples in manufacturing processes, both in R&D and production environments; additionally, one respondent described an application in which the thermocouple is used as a component in a product that the company sells to a downstream customer. Two of the firms purchase all of their assembled/sheathed thermocouples from thermocouple producers, two other firms fabricate all of their own thermocouples from bare wire, and the other six have a mixture of both purchasing finished thermocouples and fabricating thermocouples in-house.

given thermoelements can change by several degrees during the process of fabricating these wires into a thermocouple with sheathing. This change in the calibration of the thermocouple often is not stated (warranted) by the supplier, and the variation from thermocouple to thermocouple can be significant. Users control this variation in their instrumentation by establishing offset values that correlate with reference standards calibrated to NIST's primary standards. Many users feel that this random variation in calibration tolerances of thermocouples is accounted for most efficiently through internal calibrations. As a result, many firms have corporate policies of calibrating the majority, if not all, thermocouples purchased from suppliers. This is done because the use of faulty thermocouple products in user applications could result in incorrect temperature measurements which lead invariably to losses in productivity that greatly exceed the cost of a calibration test.

The second factor regards users' concerns on the quality of wire procured from wire suppliers. Wire suppliers typically fabricate each production lot of wire in one large spool that is divided subsequently into smaller spools for sale to thermocouple suppliers and users with captive production capabilities. The supplier calibrates wire lengths from the ends of each spool. Oftentimes the calibrations of wire within the spool deviate beyond an allowable tolerance range from the calibrations performed on the end lengths. Such deviations have made some users unwilling to rely on the supplier's sample calibrations as representative of the entire wire spool, which results in users performing additional calibrations internally. According to one user, substantial oversight of the operations of a wire supplier would be required before both putting greater trust in the supplier's claims on product quality and subsequently lessening its (the user's) in-house validation testing.

The third factor regards user concerns about supplier quality that are not measurement related. Several users claim that their suppliers have made errors in material handling that result in misrepresentation of thermocouple accuracy: (1) incorrect labeling or color-coding of the wires (for example, reversing the positive and negative thermoelements), and (2) making a thermocouple with two identical wires. The occurrence of such errors has driven some firms to increase its policies for the validation testing of incoming thermocouple products.

5.1.2 ISO 9000

The calibration requirements (in terms of tolerance levels or frequency of calibrations) of thermocouple users generally have stayed the same or increased slightly over the past five years, and compliance with the ISO 9000 quality control scheme has been the driving force for most

increases in calibration requirements. Certification to ISO 9000 standards is particularly important in commerce with European and Asian countries. Establishing a process for documenting the accuracy of temperature measurements to national temperature standards is an essential element in meeting ISO 9000 certification. The standards traceability process through the NIST TCP provides thermocouple users with an efficient means to comply with the requirements of ISO 9000 since the burden-of-proof for documented compliance can be obtained from the wire or thermocouple supplier.

5.1.3 ITS-90

Users have realized few net economic benefits from thermocouples calibrated to the ITS-90 compared with the previous temperature scale, the IPTS-68. The ITS-90 is more accurate than the IPTS-68, and this improved accuracy has been incorporated into the latest reference tables and functions from NIST.³³ However, users generally have not gained improvements in product performance or process efficiencies to offset the costs to incorporate the new calibration standards based on the improved NIST infrastructure technology. In fact, some users have processes that are not sensitive enough to changes in the new scale to warrant the costs of changing their instrumentation to the new standards.

These findings corroborate the views of several thermocouple suppliers during the pretest of the survey. One supplier estimates that 99 percent of all users would be unable to discern the difference in their applications between ITS-90 and IPTS-68 calibrations, and the greater accuracy incorporated in the ITS-90 calibrations would probably benefit less than one percent of users having thermocouples calibrated to the IPTS-68. Further, many of the thermocouple users undergo the conversion in their internal metrology infrastructure in order to maintain just one set of standards even though they are aware that this conversion will not provide a positive economic effect.³⁴

³³ The greater accuracy in the ITS-90 in comparison to the IPTS-68 is due primarily to the greater number (17 versus 12, respectively) of fixed points used to define the temperature scale. The fixed points refer to thermodynamic equilibria of naturally-occurring phenomena that occur reproducibly at the same temperature.

³⁴ Interestingly, many firms in the steel industry currently employ a number of large melting processes that use thermocouples calibrated to a standard temperature scale that is obsolete across other industries. The change in the international temperature scale from the ITS-48 (the International Temperature Scale established in 1948) to IPTS-68 was significant, but the steel industry determined during the changeover period that altering their processes to conform to the IPTS-68 was not economically rational. For similar reasons, the steel industry did not adopt the subsequent change in the temperature scale, the ITS-90. As such, vendors still supply

5.1.4 Transaction Costs

NIST's role in the standards traceability process reduces transaction costs with suppliers of thermocouple products since procurement disputes between thermocouple users and producers seldom occur.³⁵ Also, having NIST make the more technically-difficult, highly-accurate temperature measurements in the standards traceability scheme allows thermocouple users to establish and maintain practical (working-level) calibration standards with equipment and techniques of much lower cost than those used at the NIST Laboratory.³⁶

5.1.5 Other

Quantifying the economic effect (increased productivity or product performance) in applications involving a change in calibration requirements is very difficult. For example, a producer of aluminum products in the aerospace industry described a new aluminum alloy that saved one-third of the weight of the external tank on NASA's Space Shuttle. Improved temperature measurements in the aluminum melting process were significant in developing and manufacturing this new material. However, this was only one of many process and design factors contributing to the improved material, and quantifying the specific contribution in weight savings attributable to improved temperature measurement capabilities was difficult to estimate.

The perceived quality of the NIST Thermocouple Calibration Program has no effect on the substitution of thermocouples for other temperature measurement devices since the decision to use thermocouples in lieu of other devices is based on physical factors regarding the specific

thermocouples calibrated with older temperature standards to certain firms in the steel industry. Further inquiry shows that no other industry appears to demand this obsolete specification.

³⁵ In the one reported case, NIST was instrumental in settling a dispute between a thermocouple user and its downstream customer over relevant specifications of thermocouple calibration. In this case, the customer requested thermocouples of extreme accuracy in applications involving high temperature ranges (generally, greater than 1000 °C). NIST personnel were enlisted to help in resolving the issue, and, subsequently, NIST convinced the customer that the accuracy being sought was not attainable within the technical state-of-the-art. The customer eventually dropped its original requirement for the more stringent specifications.

³⁶ The traceability scheme is especially cost-effective in the stringent military/aerospace environment which requires a proportional method for achieving acceptable levels of accuracy for thermocouples in end-use. In this method which is a part of the Mil-Standard regimen, a 4:1 ratio for accuracy is required in each link from an end-use specification to the primary temperature standard at NIST. For example, if the end-use is a field application requiring a +/- 16 degree accuracy, then the system supplier has to warrant a thermocouple with +/- four degrees accuracy, which, in turn, is traceable to calibration measurements at NIST which are accurate to +/- one degree. Since the cost to calibrate to +/- one degree is much greater than at +/- four degrees, the traceability process provides a more cost-effective solution for each system supplier and their customers.

application; calibration factors are not a part of this decision. Also, thermocouple users receive significant benefits from the technical support available from the NIST Program.

5.2 THERMOCOUPLE INDUSTRY

Based on self-reported market share information, the sample of seven wire suppliers represents nearly 100 percent of the estimated \$160 million domestic industry, and the sample of twelve thermocouple suppliers represents over 90 percent of the estimated \$120 million domestic market.³⁷ Since over 300 domestic thermocouple suppliers actively market thermocouple products, as noted in Section 3.3.1, the industrial base of thermocouple suppliers appears to be distributed very unevenly with a few large companies and many more smaller firms.³⁸

5.2.1 Wire Suppliers

Opinions of the seven wire suppliers were mixed regarding their company's reaction to the hypothetical counterfactual scenario of NIST ceasing to provide primary calibration services. Four of the seven thought that their company would rely on foreign laboratories for similar calibration services provided by the NIST TCP. Two believed that over time an industry consensus on measurement methods would develop through a private laboratory or industry association; the emerging entity would then assume NIST's current role in providing primary calibration services. One company had no opinion.

³⁷ Wire suppliers and thermocouple suppliers were defined for this study as the first-level users of NIST's calibration services, and hence were defined as the relevant survey population for collecting primary benefit data. The respondents, seven major domestic wire suppliers (three base-metal wire and four noble-metal wire) and twelve of the major thermocouple suppliers, were identified and contacted by NIST TCP personnel to ensure their participation in the data collection phase of this study.

In the course of each interview, information was requested on the size of the wire and thermocouple markets, the importance of NIST's calibrations services, and how the industry would adjust to the hypothetical counterfactual situation in which NIST ceased to provide calibration services through its Thermocouple Calibration Program. An interview guide was prepared to ensure that all of these points were covered during the course of the conversations.

³⁸ In the course of the interviews with thermocouple suppliers, several respondents noted that a large number of so-called suppliers in the industry are actually either small, specialized producers or simply repackagers of other firms' thermocouples.

Respondents believed that interactions with a foreign laboratory would incur additional, permanent transaction costs under the counterfactual experiment. Based on previous interactions with foreign laboratories, these costs would be associated with both the administrative “red tape” and inaccessibility to scientists in the foreign laboratories. Although the quality and price of the calibration services from those laboratories are deemed comparable to NIST, the red tape and the delays in receiving services would be significant.

Those respondents anticipating that an industry consensus would develop over time ó the mean time of response was five years ó also anticipated during this interval that: (1) a greater number of measurement disputes would arise between their company and their customers in the “chaotic” business environment that would ensue, and (2) company resources would have to be devoted to the process of reaching industry consensus. Consequently, additional personnel would be needed during this five-year time interval until the domestic industry reached consensus about acceptable calibration measurements. Examples of the expected types of additional administrative costs included auditing, changes in calibration procedures, and overseas travel. The total for all respondents of the additional costs that would be needed to address all transaction costs issues, absent the NIST TCP, was \$325.0 thousand in 1996 dollars.³⁹

In addition to calibration services, the NIST TCP also provides telephone technical support to industry. Absent NIST’s services, wire suppliers would purchase similar expertise from consultants, and the total annual cost for all wire suppliers for these substitute benefits was estimated to be \$146.5 thousand.⁴⁰

³⁹ Each wire supplier was asked to approximate, in current dollars, the additional person years of effort required to cope with the additional transaction costs that would be expected in the absence of the NIST TCP. Each respondent was also asked to value a fully-burdened person-year of labor within their company. Two respondents did not offer an estimate of the value of such expected transaction costs, but both did acknowledge that such costs would exist. The mean value reported by the other respondents, by wire type, was imputed to these two.

⁴⁰ Each respondent was queried about the frequency with which they took advantage of this service, and on average it was used five times per year (the range of responses was zero times per year to once a month). Each respondent was also asked about the cost to acquire and utilize this form of NIST information, and in general the response was that the cost was minimal. The economic evaluation literature refers to such costs as “pull costs.”

Thus, based on the collective opinion of the seven wire suppliers, which effectively represent the entire domestic industry, if NIST's TCP ceased to provide calibration services, this segment of the thermocouple industry would incur \$471.5 thousand of additional personnel costs annually to continue operating at the same level of measurement accuracy.

5.2.2 Thermocouple Suppliers

Similar hypothetical cost data were collected from twelve thermocouple suppliers. Regarding an alternative measurement source in the absence of NIST's calibration services, only two respondents thought that their company would rely on foreign laboratories for calibrations. The other 10 respondents believed that an industry consensus would eventually emerge, and similar to the mean reply from the wire suppliers, the mean length of time for achieving industry consensus was estimated to be five years. One respondent mentioned that an organization "like ASTM" would eventually take on the role of the NIST TCP.

The total additional cost during the adjustment interval for all firms in the survey was estimated to be \$1,543.4 thousand.⁴¹ Also, the total additional cost for market alternatives to the technical support received from NIST is \$172.5 thousand annually.⁴² Thus, based on interviews with the 12 thermocouple suppliers which effectively represents the domestic industry on a market share basis, if the NIST TCP ceased to provide calibration services then this segment of the industry would incur \$1,715.9 thousand in additional annual costs to continue operating at the same level of measurement accuracy.

5.2.3 Summary

Viewing the wire suppliers and thermocouple suppliers together as the first-level industry beneficiaries of NIST's calibration activities through its Thermocouple Calibration Program, the economic benefits associated with these services can be approximated in terms of the additional

⁴¹ Again, no quantitative response was offered by two of the respondents, so the mean dollar value provided by the other respondents was imputed for these two.

⁴² Such interactions occur on an average of four times per year, with a range in responses from zero to once a month.

costs that the thermocouple industry (users and producers) would incur in the absence of such services. Based on extensive telephone interviews with representatives of the dominant suppliers in the two industry segments, the total annual economic benefits were estimated to be \$2,187.4 thousand in 1996 dollars. In other words, if NIST continued to provide its current annual level of industry support, then the current annual cost savings (i.e., additional transaction costs avoided) to society is \$2,187.4 thousand.

Based on qualitative responses in the survey, thermocouple consumers are very unresponsive to price changes since no close substitute products exist domestically.⁴³ The interpretation of these responses in economic terms is that the market demand for wire and thermocouples is highly inelastic. In the absence of calibration services provided through the NIST TCP (the counterfactual experiment for this case study), the wire and thermocouple suppliers collectively would incur \$2,187.4 thousand in additional costs annually to pursue alternative calibration services.

⁴³ In each of the nineteen interviews, company representative were asked their opinion about how responsive their consumers would be to an industry-wide increase in price. No supplier mentioned that their customers would substitute to foreign made wire or thermocouples.

6. ECONOMIC ANALYSIS

6.1 COST AND NET BENEFIT DATA

6.1.1 NIST Annual Expenditures and Income⁴⁴

Table 6-1 shows NIST's expenditures associated with the outputs described in Section 4.1 from government fiscal years (FYs) 1990 through 1996.⁴⁵ The line item for reference tables and functions (FY90 to FY93) accounts primarily 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, and shared the costs with the standards laboratories of eight other countries. NIST's costs accounted for about 60 percent of the total expenditures required to generate the updated reference tables. Also, costs for technical support are accounted in the line item for calibration services due to the multi-disciplined nature of work performed by personnel in the NIST TCP.

Table 6-1 also shows income from fees received for calibration services. The significant decrease in the line item for calibration income from FY91 to FY92 was due to the loss of a significant customer that set up its own calibration laboratory. Also, included in the Table as income are moneys (\$135,000 in FY92 and \$80,000 in FY94) associated with NIST's Calibration Services Development Fund (CSDF). The CSDF is derived from surcharges on calibration services, and has been used for upgrading NIST's calibration laboratories, initiating new calibration services, and providing other improvements.

⁴⁴ Information in this section was obtained from personnel in the NIST Thermocouple Calibration Program.

⁴⁵ NIST's expenditures include (1) direct, fully-burdened labor of laboratory personnel, and (2) costs of capital equipment, facilities, and maintenance that are expensed in the year incurred. Operating funds from other government agencies are negligible, and inter-governmental customers do not receive discounts on calibration services fees which otherwise would decrease NIST's costs.

Table 6-1 Expenditures and Income for The NIST TCP FY 1990 -1996 (current \$)

	FY90	FY91	FY92	FY93	FY94	FY95	FY96
Calibration Services Development Fund	0	0	135,000	0	80,000	0	0
Calibration Income	159,608	149,776	88,848	89,648	84,083	81,948	117,674
Total Income	159,608	149,776	223,848	89,648	164,083	81,948	117,674
Reference Tables and Functions	58,053	173,439	184,143	41,283	0	0	0
Test Methods and Upgrades	19,317	6,455	21,024	19,306	7,587	7,853	8,067
Calibration Services	143,019	145,992	278,015	205,992	198,524	203,988	166,646
Total Costs	220,388	325,886	483,182	266,581	206,111	211,841	174,713

6.1.2 Data for Economic Impact Analyses

Table 6-2 shows the data used for the economic impact analyses. Total expenditure data from NIST for fiscal years 1990 through 1996 have been reproduced from Table 6-1. NIST's costs are associated with the development of the ITS-90 reference tables and functions, maintenance and upgrade of test methods and test equipment, and calibration services. Since this case study uses a prospective basis for the economic evaluation, the costs to maintain the current level of calibration services in the future are forecast from 1996 costs using a six percent rate of increase to account for the expected increase in labor costs at NIST.⁴⁶

Table 6-2 NIST TCP Costs and Net Industry Benefits (current \$000)

Fiscal 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	\$2,296.8
1998	196.3	2,411.6

⁴⁶ This six-percent growth factor has been widely used in other economic impact analyses at NIST, and has been verified as a reasonable estimate by the NIST Program Office.

1999	208.1	2,532.2
2000	220.6	2,658.8
2001	233.8	2,791.8

Government fiscal year 1990 has been selected as the appropriate first year of NIST’s investments for this analysis. As explained in Section 2.3, 1990 is the year of the most recent update of the international agreements on the scale of temperature (the ITS-90) for use in science and industry, and the current technical state of thermocouple calibration measurement is based on the development of reference tables beginning in that year. NIST began its share of investments in new research in FY90 for upgrading thermocouple reference tables to ensure that U.S. firms could trace their thermocouple products accurately to the ITS-90. While pre-1990 NIST expenditures have certainly enriched the broadly-defined state of current technical knowledge for thermocouple calibrations, the most relevant aspect of this knowledge is linked to conducting and applying post-1990 research.⁴⁷ Hence, 1990 was selected as a logical starting point for the comparison of NIST’s costs to net industry benefits.

Also shown in Table 6-1 are annual estimates of net industry benefits for 1997 through 2001. These data are based on the 1996 estimate of net industry benefits totaling \$2,187.4 thousand (see Section 5.2.3). This 1996 benefit estimate was extrapolated for five years into the future using a five percent annual increase to reflect the projected costs of fully-burdened labor.⁴⁸ The five-year forecast was selected for two reasons. First, five years represents the average amount of time that respondents projected for the thermocouple industry to reach a consensus on an alternative to NIST’s calibration services in the hypothetical experiment. Second, although some respondents believed that the additional transaction costs would exist forever if companies relied on foreign laboratories and although market-based consulting substitutes for NIST’s technical assistance would similarly be continuous, truncating such net benefits to five years

⁴⁷ The investment in any technical innovation starts with a preexisting stock of knowledge, and the attainment of that knowledge is a sunk cost.

⁴⁸ This factor was obtained during industry interviews.

provides a conservative adjustment for the social return on the investments made through the NIST TCP.

6.2 MEASURES OF ECONOMIC IMPACT

The return that industry receives from investments made through the NIST Thermocouple Calibration Program has been calculated using three widely-accepted measures of economic impact. These evaluation measures are the internal rate of return, the adjusted internal rate of return and the benefit-to-cost ratio.

6.2.1 Internal Rate of Return

By definition, the internal rate of return (IRR) is the rate of discount that causes a series of costs and receipts to approach proportionate equivalence. Applying this concept to the evaluation of research projects, the IRR is the discount rate that reduces the net present value (NPV) for a stream of expenditures and net benefits to zero. Mathematically, the IRR is the discount rate r^* that satisfies the equation:

$$NPV(r^*) = \frac{(B_0 - C_0)}{(1 + r^*)^0} + \dots + \frac{(B_t - C_t)}{(1 + r^*)^n} = 0$$

where $(B_t - C_t)$ represents net benefits in year t , and n is the number of years for the research project. Reducing NPV equal to zero is comparable to a benefit-cost ratio of one (the break-even point), which allows comparisons of IRRs among projects of different sizes. The IRR equation is then rewritten as:

$$NPV(r^*) = \sum_{t=0}^n \frac{B_t}{(1 + r^*)^t} - \sum_{t=0}^n \frac{C_t}{(1 + r^*)^t} = 0$$

and,

$$\sum_{t=0}^n \frac{B_t}{(1 + r^*)^t} = \sum_{t=0}^n \frac{C_t}{(1 + r^*)^t}$$

Based on the stream of cost and net benefit data for fiscal years 1990 through 2001 in Table 6-1, the calculated value of r^* that equates NPV to zero is 0.318 (rounded).⁴⁹ In other words, 0.318 is the value of the discount rate that equates the present value of benefits to the present value of costs. This implies an internal rate of return of 31.8 percent for NIST's investments in thermocouple calibration activities.

6.2.2 Adjusted Internal Rate of Return

Under an alternative set of assumptions, an adjusted internal rate of return (AIRR) is calculated from the data in Table 6-1.⁵⁰ For example, if all of NIST's costs are referenced to 1990 using a nominal discount rate of 8.78 percent as recommended by the Office of Management and Budget, the 1990 present value of NIST's costs is \$2,015.3 thousand.⁵¹ When all industry benefits are referenced to the year 2001 using the same 8.78 percent discount rate, the 2001 present value of industry benefits is \$15,000.7 thousand. Using the AIRR, the NIST TCP is viewed as a single calibration project where an initial net investment of \$2,015.3 thousand generated, after 11 years, a consumer surplus equaling \$15,000.7 thousand. Thus, the annual compounded rate of return corresponding to such an initial investment in 1990 that culminates in 2001 is based on the value of i^* that satisfies the following relationship:

$$\$2,015.3K (1 + i^*)^{11} = \$15,000.7K$$

In this case, the calculated value of i^* equals 0.200 which means that the AIRR for the NIST TCP is 20.0 percent.

⁴⁹ The data in the first year of the benefit-cost stream are referenced to time $t=0$ in the IRR equation as well as for the other economic measures.

⁵⁰ The adjusted internal rate of return is similar to the overall rate of return suggested by Rosalie R. Ruegg and Harold Marshall, *Building Economics: Theory and Practice*, (Van Nostrand Reinhold: New York, 1990). An example of the AIRR, also known as the compound rate of return, is the annual yield earned on a \$100 bank deposit. Interest is earned each year on the original \$100 plus compounded interest.

⁵¹ See: "Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs," Office of Management and Budget (OMB), Circular No. A-94, 29 October 1992. OMB recommends both a seven percent real rate of discount for federal project evaluations and an approximation of inflation based on the implicit price deflator of Gross Domestic Product. Based on data from the Federal Reserve Board over the last four available quarters, the implicit price deflator is 1.78 percent which is used to convert the real discount rate of seven percent to a nominal rate of 8.78 percent.

6.2.3 Benefit-to-Cost Ratio

A benefit-to-cost ratio (BCR) relates the present value of NIST TCP costs to resulting industry benefits. Costs and net benefits are deflated to 1990 using an 8.78 percent rate as in the AIRR calculation. The BCR is 2.95 using 1990 present values of costs (\$2,015.3K) and benefits (\$5,943.9K).

6.3 MEASURE OF ECONOMIC IMPORTANCE

One way of approximating the economic importance of thermocouples in the U.S. economy is to use the U.S. Department of Commerce (DoC) Standard Industrial Classification (SIC) system and Input/Output statistics. Based on SIC descriptions, three 4-digit industries (3823, 3824, 3829) include thermocouple producers. The composite sales in 1987 for these SIC codes were \$3.6 billion in components and \$4.0 billion in capital equipment.⁵² These components and equipment, in turn, were inputs for the manufacture of \$2.462 trillion of manufacturing output.

A quantification of the economic importance of thermocouples on domestic industry is made by using the 1996 estimated total domestic market value (\$280 million) for wire and thermocouple assemblies and the 1987 Input/Output data. If the input/output relationship between the aggregate industries in SICs 3823, 3824, and 3829 and total manufacturing output hold for the more narrowly defined industries that they compose, then thermocouple products could affect as much as \$81.0 billion in manufacturing output.⁵³

6.4 ECONOMIC RETURN FOR UPGRADING REFERENCE TABLES TO ITS-90

The survey provided evidence that the vast majority of thermocouple users — including users with high accuracy requirements — have attained few net benefits in using thermocouples

⁵² Based on a phone conference with a representative of the DoC Bureau of Economic Analysis. The Input/Output data is based on 1987, the most recent year that such statistics are available.

⁵³ Using ratios of total direct requirements: \$7.6 billion in components and capital equipment is to \$2,462 billion in manufacturing output, as \$250 million in thermocouple products is to x dollars in manufacturing output. Solving for x equals \$81.0 billion. It is recognized that this analysis is somewhat faulty due to the use inconsistent data because the \$250 million figure is based on 1996 dollars while the other data is based on 1987 dollars, which is the most currently available data from the USDOC.

calibrated to the ITS-90 compared to thermocouples calibrated to the IPTS-68.⁵⁴ Since the upgrade of thermocouple reference tables and functions to facilitate the conversion from IPTS-68 to ITS-90 is one of the outputs being evaluated in this case study, a follow-up analysis was performed to determine if insights could be gained for future strategic planning at NIST.

Two sets of investments have been made in the conversion of standards for thermocouple calibration that are consistent with the improvements in the technical state-of-the-art of the international temperature scale from IPTS-68 to ITS-90. The first set of investments has been made collectively by agreements among NIST and the standards laboratories of eight other countries, and these investments led to the upgrade of the reference tables and functions for thermocouples calibrated to ITS-90.⁵⁵ The second set is the costs incurred by all organizations (users and suppliers involved with thermocouple measurements) that converted internal measurement infrastructures to the ITS-90. Using the anecdotal results from the survey of thermocouple users in this case study, the intrinsic payback on both sets of investments has been poor.

The investment decision by NIST to upgrade the reference tables was driven completely by international agreements on the change in the temperature scale. While the economic returns to industry on this investment to date have not been significant, the original decision must be assessed relative to the economic consequences of not having made the investment. In other words, for the purpose of this case study, the evaluation of economic impact is posed in terms of the likely scenario and qualitative outcome on domestic industry if NIST hypothetically had not invested and participated in upgrading the thermocouple reference tables to ITS-90.

The remainder of this section describes four primary reasons offered by NIST TCP personnel to justify the original investment decision. These views have been corroborated by representatives in the thermocouple industry in follow-up interviews.

⁵⁴ Theoretically, the greater accuracy embedded in the improved temperature scale (ITS-90) would allow thermocouple users with high accuracy requirements to obtain enhanced product performance and process efficiencies since the ITS-90 is more accurate thermodynamically than the IPTS-68.

6.4.1 International conformity to the temperature scale

The primary motivation for NIST's original investment decision made cooperatively with the standards organizations of the eight other countries was to keep all the world's thermocouple users and producers on the same temperature scale. This decision contributes to consistency in the national standards for temperature among the U.S. and other industrialized countries that seek leading-edge measurement technology to augment advanced technology products.

Under the hypothetical scenario of NIST not participating in the joint investment, U.S. companies would likely have risked being unable to sell their products into certain international markets. U.S. firms would still be using thermocouples calibrated to the ITS-68 while the other industrialized countries would require products conforming to national standards based on the ITS-90. The likely consequence is that U.S. firms' products incorporating temperature measurements with IPTS-68 thermocouples would not be welcomed as imports into foreign markets having temperature specifications linked to the ITS-90.⁵⁶ For example, most foreign companies now specify ISO 9000 product standards which require ITS-90 compliance. Therefore, maintaining national standards consistent with those of other countries that use high technology products provides significant competitive advantages internationally.

6.4.2 Other Temperature Measuring Devices

The ITS-90 affects all devices for measuring temperature. Many organizations that use thermocouples also use other types of temperature measuring devices for internal applications. Given the over-arching acceptance of the ITS-90, the temperature measurement community has agreed that investments in upgraded calibration knowledge were necessary for all temperature measurement devices. If such investments were not made for every device, then users of would be faced with making in-house temperature measurements with more than one temperature scale. Certainly, the use of more than one temperature measurement system simultaneously would not

⁵⁵ NIST took the lead role for technical work involved in the conversion process, and the other countries contributed calibration test results.

⁵⁶ The consequences are much greater for the population of thermocouple users in comparison to the smaller population of domestic wire suppliers and the thermocouple suppliers since the product sales outside of the U.S. for the latter set of producers are not significant.

be rational economically or practically for user organizations. Therefore, the decision to make the investment in upgrading the thermocouple reference tables was made for consistency with similar upgrades of calibration know-how for other temperature measuring devices.

6.4.3 Long-Term Benefit Horizon

A long-term “benefit horizon” is always assumed in investment decisions by NIST. Part of NIST’s charter is to predict infrastructure technology for the future, not just for meeting current needs of users. Accordingly, NIST regularly undertakes investments for increasing the technical state-of-the-art with the understanding *a priori* that many users will not (or be unable to) take advantage of the improved measurement technology until they need or obtain better control over their internal product and process capabilities. Determining when these needs arise is difficult to predict, so the ready availability of the NIST-developed infrastructural know-how overcomes this problem.

Another reason for early insertion of advanced infrastructure technology is that typically a significant amount of time and resources is needed for both conducting the requisite R&D and implementing block changes in the standards agreement process. In the case of developing the improved reference tables calibrated to ITS-90, a three-year effort on the part of NIST was required to develop the R&D followed by one year for incorporation into the ASTM standards.

6.4.4 R&D Leadership Role

NIST’s lead role in developing the improved infrastructure technology provides domestic thermocouple users and suppliers with certain benefits not shared by their counterparts in other countries. Since most of the technical work was performed and promulgated through NIST, which has a stellar reputation for quality and independence, the domestic thermocouple community has assurances of a sound technical foundation for the infrastructure technology outputs. Alternatively, this community might have less acceptance of similar outputs derived from foreign laboratories having technical capabilities that are not as firmly established. Sponsorship of similar infrastructure technology from foreign laboratories that are comparable technically with

NIST could have negative effects on the competitiveness of the domestic thermocouple industry.⁵⁷

⁵⁷ One user respondent suggested that, in lieu of the NIST TCP, many domestic users would buy thermocouple products from firms in the country of the lead standards organization instead of from U.S. firms because of the technical intricacies involved between a standards organization and the first-tier thermocouple producers. Obviously, this procurement posture would not bode well for the supply side of the domestic thermocouple industry.

7.

CONCLUSIONS

7.1 ECONOMIC IMPORTANCE OF THERMOCOUPLES

The analysis in Section 6.3 shows that thermocouples comprise a relatively small percentage of cost in higher product structures but their economic importance has a large rippling effect in the overall manufacturing economy. In other words, thermocouples provide an efficient means for performing the temperature measurement function that is essential in many industrial applications, and thermocouples are relatively inexpensive compared with other component items in higher-level assemblies of products and processes that incorporate thermocouple calibration know-how. Since temperature is the most widely-used indicator in industrial processes, the implication is that thermocouples are significantly important in the domestic manufacturing economy.⁵⁸

The relatively low cost of thermocouples is attributable, in part, to the effectiveness of the NIST Thermocouple Calibration Program. This case study has proven that both industrial users and suppliers of thermocouples believe that the NIST TCP provides the most efficient means for incorporating the complex technology embedded in practical measurements of temperature made with thermocouples. Therefore, society realizes significant benefits from investments made by NIST which result in the relatively low costs for both thermocouple products and measurements made with thermocouples.

7.2 ECONOMIC IMPACT OF THE NIST TCP

Economists and policy makers generally use internal rate of return measures to estimate the social rate of return (SRR) for on-going or completed research projects in the public sector. In this case study, if the 31.8 percent IRR calculated in Section 6.2.1 is above NIST's hurdle rate (minimum acceptable rate of return) then the investments in NIST thermocouple calibration research and related activities are worthwhile from a social perspective. Also, in comparison to

⁵⁸ The thermocouple is the most widely-used among other electronic devices (RTDs, thermistors, etc.) for sensing temperature. Temperature, in turn, is the most widely-used among other indicators (force/displacement and optical radiation) for physical sensing. Physical sensing, in turn, is the most prevalent among the other classes of sensors (chemical, biosensor, and microsensor). See Richard C. Dorf, ed., *The Engineering Handbook*, (IEEE Press), 1996, pp. 1484-1489.

the average hurdle rate of about 12 percent for corporate technology projects, investments in the NIST TCP are beneficial from a general economic standpoint.⁵⁹

The IRR is often confused with the adjusted internal rate of return (AIRR). Both measures are used in financial analyses but the type of cash flow pattern associated with the AIRR occurs neither in an R&D project, in general, nor in the case of NIST TCP-related research and activities, in particular. Therefore, the AIRR is not directly comparable to the IRR discussed in the economics literature.

Several factors have been incorporated in this study to characterize the 31.8 percent IRR as a conservative estimate of NIST's economic impact on industry. These factors are:

- (1) Industry benefits pertinent to thermocouple suppliers are underestimated since the reported benefit data from the 12 sample suppliers (having about 90 percent cumulative market share based on self-reported data) was not extrapolated to the many other firms (having 10 percent cumulative market share) in the industrial base.

Indeed, according to recent internal records of the NIST TCP, at least 32 additional thermocouple suppliers have paid for calibration services from NIST. Benefits related to these smaller suppliers have not been accounted since the estimate of total benefits is based on market share – not total number of companies. Potentially, these smaller suppliers collectively would incur significant costs under the hypothetical experiment used in this analysis.

- (2) Only the first two major types of benefits (research efficiencies and transaction cost savings) have been included in this IRR calculation because these economic impacts were more direct and easier to quantify. Disregarding the third type of benefit (users' product and process improvements) also underestimates industry benefits.
- (3) The 1997 starting point also adds to a conservative benefit estimate since industry attains benefits from NIST's investments in prior years (1990-1996) of the economic framework for this study. The 1997 starting date was selected because of the study's prospective methodology as explained in Section 4.4.2.

⁵⁹ J. Poterba and La. Summers, "A CEO Survey of U.S. Companies' Time Horizons and Hurdle Rates," *Sloan Management Review*, Fall 1995.

- (4) The “bottom line” annual costs of the NIST TCP are much less than the reported expenditures since the policy of NIST is to charge user fees to recover the marginal costs of calibration services. Additionally, surcharges have been applied through the CSDF to help pay for the underlying research and equipment for improved thermocouple calibration know-how.

Offsetting NIST’s costs with these income items would result in an attribution of all the social benefits to only a portion of the total costs in this case study. Therefore, conservatism is built into the calculations of the economic measures since NIST’s costs have not been offset by its income. From a more liberal economic viewpoint, the estimated return on NIST’s investments would be higher if expenditure data were offset with income.

Therefore, the 31.8 percent IRR is a lower bound estimate of the industry benefits attributable to NIST’s investments in thermocouple calibration.

7.3 POTENTIAL IMPROVEMENT IN THE TRACEABILITY PROCESS

The findings in Section 5.1.1 show that many thermocouple users having requirements of high accuracy rely on calibration tests performed internally rather than from statements of accuracy obtained from their suppliers. Many users claim that internal calibration testing is both necessary due to the random nature of thermocouple calibrations and an efficient means of maintaining process control with applications having stringent accuracy requirements. However, there is ample evidence that, to some extent, the efficiency in the standards traceability scheme headed by NIST is being degraded since users cannot rely totally on their suppliers to provide the correct representations of calibrations for thermocouple products. This is a sign of market failure in thermocouple commerce due to redundant calibration testing being performed by certain users on purchased lots of wire or finished thermocouples that are calibrated previously to standards by the supplier.⁶⁰

The root cause of this non-optimal situation appears to derive from issues about assurances of product quality from suppliers of wire and thermocouples, and these issues are not linked directly with measurement-related know-how from the NIST TCP. However, NIST could

⁶⁰ In the economic literature, the term “market failure” refers to a malfunction in private-sector activity that results in a suboptimal allocation of resources.

use its neutral role to help industry overcome this problem. Possibly, assistance from the NIST Manufacturing Engineering Laboratory would identify ways for industry to improve product uniformity so that the implementation of the traceability process can approach greater levels of efficiency. An analysis should be performed to determine the economic payoff to users for investments in manufacturing technology that would enhance the quality of thermocouple products.

7.4 LESSONS-LEARNED FROM IMPLEMENTING ITS-90

The situation described in Section 6.4 regarding the conversion to the most current international temperature scale, the ITS-90, provides some interesting insights on the timing of investments in leading-edge infrastructure technology. All of the reasons provided by NIST for the investment in upgraded reference tables have economic validity with respect to their intended objectives, but a net economic gain has not resulted from the overall investment because the key benefits (improved product performance and process efficiency) affecting thermocouple users have not been realized. However, NIST made the correct decision to invest in the innovative measurement technology (the updated reference tables) in response to an international agreement to change the temperature scale. U.S. industry would likely have suffered negative economic consequences if NIST had not made this investment. The failure to realize net positive economic benefits resulted from a mismatch in the timing of when this infrastructure technology can effectively meet the practical needs of industry (thermocouple users).

In retrospect, the proper course of action might have been to delay the international agreements on updating the International Temperature Scale until industrial users' products and processes would be projected to absorb more-readily this innovation in infrastructure technology. In turn, the investments in updating calibration technology — such as the thermocouple reference tables — could have been postponed. From an economic perspective, such investments would be more effective if better intelligence were available on the timing of the economic payoff including dependency on foreign trade. Such an analysis would have included estimates on the number of users expecting to benefit from the improved ITS-90 based calibrations and the timing of when such users' requirements would emerge. In other words, investments in state-of-the-art

technology infrastructure must coincide as closely as possible with the evolution of industrial demand and, hence, corporate strategy.