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The National Measurement System for Temperature

James F. Schooley

Institute for Basic Standards
National Bureau of Standards
Washington, D. C. 20234

December 1975

Issued August 1976

DEPARTMENT OF COMMERCE
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U.S. DEPARTMENT OF COMMERCE, Elliot L. Richardson, *Secretary*
Edward O. Vetter, *Under Secretary*
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NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Acting Director*

THE NATIONAL MEASUREMENT SYSTEM
FOR TEMPERATURE

J. F. Schooley
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FOREWORD

CONCEPT OF A NATIONAL MEASUREMENT SYSTEM

"Concurrently with the growth and industrialization of this nation, there has developed within it a vast, complex system of measurement which has made possible the very growth that brought the system into being. This National Measurement System (NMS) stands today as one of the key elements in a worldwide measurement system that links all major nations together in a consistent, compatible network for communication and trade.

"Briefly stated, the essential function of the NMS is to provide a quantitative basis in measurement for (i) interchangeability and (ii) decisions for action in all aspects of our daily life -- public affairs, commerce, industry, science, and engineering.

"Our National Measurement System is one of a number of mutually interacting systems within our technologically based society that form the environment in which the individual citizen must live and function. Familiar examples are the communication, transportation, educational, medical, and legal systems, all of which may be included under the general heading of social systems.

"In view of the demonstrated value of the systems approach for the understanding and improvement of hardware such as computers and weapons, some of these social systems are being subjected to the same type of analysis. The National Measurement System, which evolved in this country with little formal recognition as a system, is now being examined in this way at the National Bureau of Standards (NBS) which undertook the study of NMS partly because of a growing realization of the all-pervasive nature and great economic importance of the nation's measurement activities, and partly because of the challenge to NBS in putting its splendid new facilities to optimum use for the benefit of the nation. Such optimum use can be approached only when NMS, of which NBS is a central element, and the services it requires for effective operation are sufficiently well understood.

"Because the government has wisely refrained from assigning leadership of NMS to NBS by law or executive order, the Bureau of Standards must maintain this leadership through demonstrated competence and general acceptance of its capability. This situation presents both a challenge and a responsibility. The NBS must make a continuous effort to understand the structure and operation of the NMS, to assess the value of its services for national objectives, and to develop means for evaluating its effectiveness.

"Our study of the National Measurement System is still in its early stages. There remains much work to characterize inputs and outputs, interactions with other social systems, involvement with national objectives, the functions of NMS elements, and couplings between the elements."

This description of the National Measurement System was first published by Dr. R. D. Huntoon in Science, 158, 67-71, October 6, 1967. *Dr. Huntoon at that time was director of the Institute for Basic Standards, of the National Bureau of Standards. For the reasons stated in the above quotation, Dr. Huntoon began and fostered systematic studies of the National Measurement System of which the following work is a part.*

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ABSTRACT

The National Temperature Measurement System reaches quite literally into all phases of American life. Comfort control in home, school, office and factory, health care, manufacturing, food preparation and storage, and all forms of powered transportation are just a few of the many facets of America's human activities that depend for their trouble-free operation on the existence of reliable thermometry.

The Heat Division of the National Bureau of Standards collaborates with the national laboratories of other nations in establishing an International Practical Temperature Scale which represents thermodynamic accuracy insofar as current scientific practice permits. The NBS is the only U.S. agency bearing this responsibility; in addition, only the NBS is responsible for disseminating the International Scale to U.S. scientific and technical activities.

The Study of the National Temperature Measurement System shows that the NBS continues to contribute energetically to the quality of the International Scale. It further indicates that NBS maintains a consistent and deliberate effort not only to provide access to the Scale at the several levels required by U.S. science and technology, but also to participate in solving special problems in thermometry. These are problems for which the nature of NBS as an objective, expert resource in thermometry uniquely qualifies it to furnish effective, practical solutions.

In briefly describing the many aspects of the National Temperature Measurement System, this Study attempts to portray its great diversity of products, services, and people. The System is largely organized, as might be expected, for the purpose of economic gain; the NBS enters the picture only in those areas where highly accurate or intricate thermometry is essential.

THE NATIONAL MEASUREMENT SYSTEM FOR TEMPERATURE

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Heat Division
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EXECUTIVE SUMMARY

Temperature is a well-defined, basic scale quantity. It is perhaps the most commonly-measured of all the physical units (the possible exception being that of time). This very ubiquity, however, has a double effect. We desire (in principle) that we should have access to very accurate thermometry, but, on the other hand, we tend to take the measurements for granted, so that our practice of thermometry is often of poorer accuracy than we suspect.

The direct temperature measurement and control industry is a large one by any standards, including several dozen multi-million dollar firms. The amount of economic leverage which thermometry exercises is multiplied greatly, however, by the fact that good thermometry is essential to the commercial success of many industries, such as semiconductor, steel, chemicals and plastics manufacturing, medical testing and care, and precision instrument manufacture and use. Temperature is acquiring a new urgency in other areas as well, with the tremendous demand for new sources of energy; with the more stringent pollution and efficiency requirements under consideration for automobiles and aircraft; with the heavy new demands for safety and output being placed on nuclear power reactors; and with the desire to map and exploit the ocean's depths.

In briefest terms, NBS is meeting the heaviest of today's demands. The temperature scale is known and can be transmitted on demand with an accuracy which is satisfactory for most purposes in the range 20-1300 K. The calibration services offered by NBS for platinum resistance thermometers, for liquid-in-glass thermometers, and for thermocouples answer most of the direct needs for accuracy in that range.

Yet many human activities suffer a lack of adequate thermometry, even in the same 20-1300 K range. The particular reasons for this situation are numerous, but they come down to a few general problems:

1) Adequate thermometry exists, but it is not applied to the problem. The whole field of practical medicine suffers from this difficulty.
2) The type of measurement which is needed is not one for which calibration rationale exists. Fast-response, hostile environment, and geometrically-constrained thermometry requirements exist in many fields of endeavor; many of these are noted in the full report.
3) The calibration procedure which exists is often expensive. The drugstore thermometer is an example of this problem—a $10 calibration of a $1 thermometer is simply impractical.

Adding to these problems those which exist where the temperature scale is *not* adequate to today's needs gives one a fair picture of the opportunities which lie before NBS in thermometry today.

Again in brief terms, NBS thermometry programs lie in several general areas:

1) Generate an adequate scale below 20 K and above 1300 K.
2) Devise calibration and temperature standardization procedures which will solve people's problems, rather than simply transmitting the highest attainable accuracy.
3) Participate in the development of thermometry methods in areas where glaring weaknesses exist.

The NBS temperature measurement activities impinge on the U.S. temperature measurement system directly in a multitude of ways. The most obvious, of course, is through the calibration of precise temperature sensors. A second interaction is through NBS participation on voluntary standards committees; that is a quite important activity, because it serves both to communicate to others expertise and data originating at NBS and to alert the NBS staff to problem areas. A third major interaction with the temperature community arises through NBS staff participation in the development of measurement methods—in general, this interaction occurs directly with one or more technical thermometry groups in industrial or scientific laboratories. Many such instances are detailed in the report.

The National Measurement System study has been a valuable tool in our effort to focus our limited resources on the most pressing and susceptible problems. We intend to continue to use this approach to assess and, as necessary, to modify the NBS temperature program.

1. INTRODUCTION

As the stewardess turned and walked toward the back of the plane, it banked sharply and pitched forward. The pretty woman in Seat 3A clutched her baby tightly and glanced anxiously at her husband.

"What is it?" she asked.

"I don't know, replied her husband as he instinctively steadied her and their baby with one hand and placed the other on their sleeping son to his right. "We are surely going down in a hurry".

The plane dropped rapidly. Looking out of the side window, the frightened couple could see the rising lights of a city. The woman gasped as the plane pulled up just as a crash seemed inevitable. The lights of a runway wheeled into view and disappeared behind the nose of the aircraft as the wheels bumped onto the pavement. A flashing red light appeared beside the plane, testifying to the presence of an emergency vehicle beside them.

Then, as the plane began to slow, the voice of the pilot sounded over the cabin intercom. "We're sorry for the hasty landing, folks, but we received an engine overheat alarm up there, and the book says 'Bring it down while you still have two wings'. We'll check it out now and, if it was a false alarm, we'll be back in the air in no time. Meanwhile, please sit back, relax, and listen to some music".

The woman's husband, a physicist, employed at the National Bureau of Standards, audibly released his breath and, noticing that his hands were still pressing forcibly on his wife and children, he consciously released his grasp. Leaning back in his seat, he pondered the rush of events which had followed the placid removal of his dinner tray by the stewardess. Noting the absence of any visible disturbance in the engine nacelles looming darkly from the wings on either side of the passenger compartment, he wondered what the real cost of this particular engine overheat alarm sensor malfunction might be. First, there was the extra landing—jet fuel, extra crew time, airport fees. Then, whatever missed appointments might take place as a result of the inevitable delay here—wherever they were.

The story related above [1] is true in all of its elements. It points up several features of the tale we want to tell in the coming pages—temperature sensors *do* fail, in spite of careful manufacture, selection, and calibration; these failures *are* costly, both in dollar and in human terms; and it *is* in part the job of the thermometry program at the NBS to consider whether such problems can be alleviated and the costs reduced by basic or applied research or other services which might be undertaken by the NBS.

This study is part of a large enterprise [2] which has a broad goal—to document the extent to which the NBS is meeting its statutory responsibility to [3]

1) provide a central basis for a complete and consistent system of physical measurement in the U.S.,
2) coordinate that system with those of other nations, and
3) furnish essential services leading to accurate and uniform physical measurement in science, industry and commerce.

It is a natural step to separate the NBS activities according to the various units of measurement, and to present the discussion for each unit along the lines sketched in the previous paragraph. Thus, this portion of the overall study will discuss the extent to which the NBS is meeting its statutory responsibilities in the area of temperature measurement.

The study of thermometry has a long and honorable history. Undoubtedly, the fundamental significance of temperature to thermodynamics and its importance to the study of material properties has led to its preeminence as a subject of painstaking research and careful national and international deliberation. For whatever reason, however, temperature is far and away the most widely studied of all the standard units. Thus we shall find that the conceptual bases for temperature and for its measurement are soundly placed, and that there is very substantial agreement on a well-developed temperature scale. Furthermore, the National Bureau of Standards has a distinguished history of leadership in thermometric affairs, and we shall see that the NBS continues today to participate in the expanding frontier of thermometry.

The very ubiquity of thermometry, however, has led to two problems which this study will treat: one problem is that so many temperature measurements are made and so many thermometry facilities exist, that even cataloging them, let alone their analysis, is nearly impossible; the other is that the familiarity of thermometry has, in many cases, dimmed people's appreciation of the desirability of characterizing the accuracy of a given temperature measurement and of the possible importance of that accuracy to the problem at hand.

There are other questions which we shall address as we explore the manifold components which make up the national measurement system for contact thermometry. Among these are whether the people who want to measure temperature have available to them the thermometric equipment and the accuracy required for a successful solution to the problem at hand, what role the NBS can play in solving difficulties which arise in those situations, and whether adequate mechanisms exist by which present deficiencies and future needs in the measurement system can be evaluated and overcome through the NBS's efforts.

2. STRUCTURE OF THE NATIONAL TEMPERATURE MEASUREMENT SYSTEM

In this section the reader will begin to see the awesome proportions of the U.S. thermometry community. This giant takes on some of the aspects of a bustling city, with its own map, currency, banks, factories, emergencies, and policemen.

The reader can only find his way through the community with the aid of maps--the basic scale of temperature and the various thermometry specifications and regulations issued by the General Conference of Weights and Measures, the American National Standards Institutes and others of the "city fathers". The currency of this realm is composed of temperature measurements at all levels of accuracy. The "really *big* money"--the highest accuracy, International Practical Temperature Scale measurements--is rarely seen outside of the banks (the major calibration laboratories), but no one doubts that the city needs the "big money" just as much as it needs the small change of less precise measurements which is readily seen throughout the city's factories and homes.

We all live in this community, we buy thermometers at home or at work, we measure temperature more or less accurately, we complain when we are "shortchanged" by unnecessarily inaccurate or expensive thermometry and we exult when a shiny new coin of a more useful or less expensive measurement comes into circulation. For the next few pages, then, let us take a quick tour through Thermometry, USA--our own hometown!

2.1 Conceptual System of Temperature

Temperature, like the quantities mass and length, has a firm physiological basis, so that the history of thermometry reaches to the ancient Greeks [1]. By the beginning of the 17th century, Galileo had demonstrated an air thermometer, and before that century ended, there were calls for thermometric fixed points and for standardization! Fahrenheit, a Pole, and Celsius, a Swede, were among the early contributors to temperature scales in the region between ice and steam temperatures.

Efforts to discuss temperature and thermometry in terms which are scientifically recognizable today resulted, in the 19th century, in the definition of temperature as "the thermal state of a body with reference to its ability to communicate heat to other bodies" by Maxwell [2]. Lord Kelvin (then William Thomson) placed the evaluation of temperature (or "thermometry) on a sound thermodynamic basis by considering the efficiency of reversible heat engines [3]. This method, which is based on Carnot's concept of heat engine cycles, permits the definition of a thermodynamic zero of temperature.

Clearly one can define a temperature scale by defining an absolute zero of temperature and by simultaneously assigning a numerical value to the temperature at which a particular natural phenomenon occurs. Alternatively, he can simultaneously assign numerical values to the temperatures characteristic of two separate phenomena [4]. Either technique defines the size of the unit of temperature and evaluates the scale at two temperatures, thus leaving the temperatures at which all other phenomena take place as quantities to be determined by experiment.

While the science of thermodynamic temperatures was slowly advancing, the technologist busily set up temperature scales on which the available natural phenomena of melting ice, boiling water, body temperature and the like could be evaluated. As we mentioned above, Fahrenheit and Celsius were involved in this work, although they were certainly not alone. As one might suppose, the scales which were proposed were suggested for diverse reasons, and their evolutions were not necessarily predictable. These efforts resulted in the Fahrenheit scale, chosen so that 100 degrees separated human body temperature from that of a cold winter day, and the Centigrade scale, which was defined so that one hundred degrees separated water's freezing and boiling points at 0 °C and 100 °C, respectively. The Fahrenheit scale was in use in the 18th century, but the Centigrade scale was not produced until 1850.

The thermometric principle of defining the temperature scale by assigning values to the temperatures of two natural phenomena (in this case the Centigrade scale assignments) was chosen by the 31-member Seventh General Conference on Weights and Measures in 1927 as the basis for the first International Temperature Scale.(ITS). The pracitcal aim of the General Conference in introducing the Scale of 1927 was to provice a convenient reproducible scale for general use. The achievement of thermodynamic accuracy was a difficult experimental problem, and the General Conference hoped to enhance work-a-day thermometric accuracy by defining the scale in terms of platinum resistivity, thermocouple emf, and optical pyrometry rather than in terms of gas thermometry or other techniques capable of thermodynamic accuracy. This idea appears to have been quite a good one [5].

Because of the insight which it gives into the nature of thermometry, the ITS of 1927 is included as Appendix C. We might note that the Scale was based upon a proposal jointly presented by NBS, NPL (Great Britain) and PTR (Germany), and that the U.S. announcement was written by G. K. Burgess during his tenure as Director of NBS [6].

The General Conference considered that the ITS needed its own group of specialists, so an Advisory Committee on Thermometry was formed in 1933 to address these problems directly. The Advisory Committee prepared a new (and, above 630 °C, an improved) version of the ITS in 1948 which the International Committee on Weights and Measures recommended to the Ninth General Conference. The new scale was adopted; it retained the definition of the melting and boiling points of water as 0 °C and 100 °C, although the name of the unit was changed to Celsius to honor the pioneering Swede [7]. Furthermore, the thermodynamic scale was given the name of Kelvin and defined by setting an absolute zero of temperature and assigning the value 273.16 K to the triple point of water [8].

The awful truth that the practical scale unit (°C) differed from the thermodynamic unit (the degree Kelvin) resounded in the world's halls of state for twenty years. In 1968, however, the 13th General Conference at last adopted identical bases for the two scales. Henceforth, the Kelvin would be defined as 1/273.16 of the temperature of the triple point of water, and the degree Celsius was given an equal value by defining Celsius temperatures as $t = T - T_0$, where T is the thermodynamic temperature in Kelvins, and $T_0 = 273.15$ K [9].

We should note here that the satisfaction which thermometricians feel in knowing that International Practical [10] Temperature Scale (IPTS) temperatures are (potentially, at least) completely equivalent to thermodynamic temperatures must be tempered by the knowledge that advances in thermometric research will likely result in periodic adjustments of the scale values, with consequent adjustments required in "science and industry" [11].

The latest revision of IPTS [12], in 1968, continues the practice of assigning values to a number of triple points, boiling points, and freezing points. The usefulness of these defining fixed points lies in their ease of use as check points against which a given thermometer may be calibrated. In fact, few of them *are* easily used [13], and consequently their practical value is diminished. Recently some progress has been made in the "fixed point business", however; this will be discussed in Section 4.

2.2 Basic Thermometry Infrastructure

2.2.1 Documentary Specification System

2.2.1.1 Standardization Institutions

There are five hierarchies of standards bodies which are concerned with thermometry. One of these is headed by the General Conference on Weights and Measures (C.G.P.M.), and it is devoted to the elucidation of the Kelvin Thermodynamic and of the International Practical Temperature Scales. A second hierarchy generates many consensus standards for use in commerce, industry, and other "public" situations, ultimately leading to the International Standards Organization and the International Electrotechnical Commission. Thirdly, there are various professional and manufacturing associations. A fourth hierarchy is comprised of U.S. regulatory agencies; and finally, there are government and commercial standards laboratories. (We should note that, although our own concern is temperature and thermometry, each of these hierarchies considers many other units as well.) The first, fourth, and fifth of these hierarchies are primarily concerned with physical measurements *per se* and are discussed in Section 2.4. The remaining two are described here.

a) Commercial Consensus Standards

The measurement of temperature in commerce and industry has been a long-time concern to professional associations and to organizations which have arisen solely to promote standardization. The latter group has achieved wide acceptance because it encourages the participation of manufacturers of thermometric apparatus, users of such equipment and objective third parties; we shall discuss this latter group first.

Three international bodies are concerned with standards used in commerce, and their recommendations are significant because many countries accept them as legally binding for national and international trade. These bodies are the International Standards Organization [14], the International Electrotechnical Commission, and the International Organization for Legal Metrology [15]. The American National Standards Institute [16] provides the U.S. representation to the ISO and IEC, and it, in turn, derives much of its detailed recommendations from the American Society for Testing and Materials [17]. Figure 2.2A shows a sketch of these organizations.

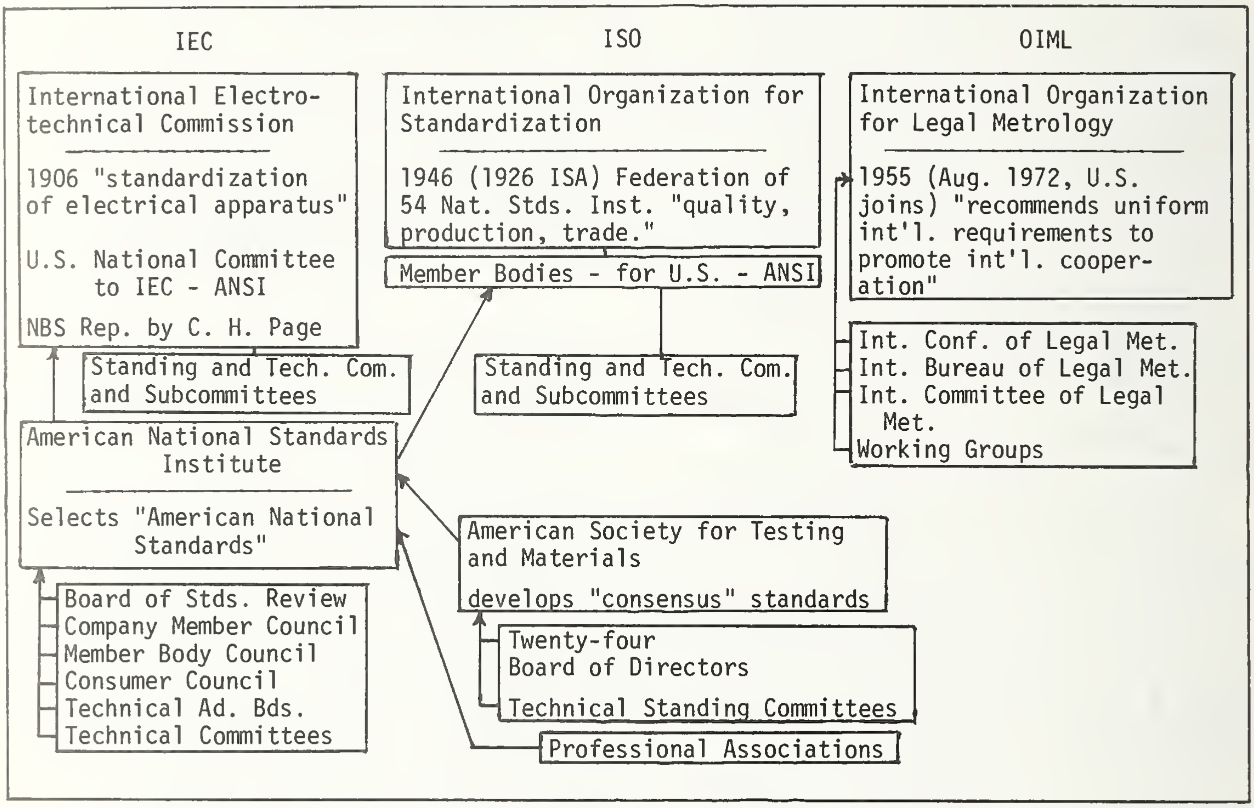

FIGURE 2.2A. Sketch of the structure of the IEC, the ISO, and OIML.

The work of these standards groups is to develop standards for all manner of devices, test methods and test equipment. The IEC and ISO seek agreements which will facilitate international trade--in fact, some nations (most recently Denmark) [18] automatically accept these international Standards as legally binding within their own boundaries. The United States has recently joined OIML, whose function is to recommend uniform metrological requirements, which relate to legal standards in its member nations.

The most difficult problem which these groups face may well be that they have rather completely overlapping "jurisdictions", so that each may more or less simultaneously write conflicting recommendations regarding essentially identical materials or instruments. W. A. McAdams Director of ASTM, pointed out recently that the writing of international standards is more difficult in cases where the individual member nations have international standards, since these generally conflict in their details; McAdams noted a trend toward standardization first at the international level and advised ASTM to "Reexamine its role and effort in light of these trends" [19]. If, in fact, international standardization were to precede national standardization, rather impressive coordination problems might well develop. Currently ASTM has over 20,000 members who serve on 115 committees, and these members would no doubt continue to be interested in the details of any international standards which concern the products of their companies.

Also, NBS is involved in commercial standards activities, at several levels. Individual staff members serve on committees and subcommittees of both the U.S. and the international bodies; a partial listing of such service is included as Appendix D.

b) Professional and Trade Associations

The second main category of voluntary standards bodies comprises the professional associations. This category can be further subdivided into scientific associations and commercial associations. Among the former group may be included the International Union of Pure and Applied Physics (IUPAP), the American Institute of Physics (AIP), the International Institute of Refrigeration (IIR), the National Conference of Standards Laboratories (NCSL), and the National Conference on Weights and Measures (NCWM). The latter group includes (but is certainly not limited to) the American Society for Mechanical Engineers (ASME), the Electronics Industries Association (EIA), the Institution for Electrical and Electronic Engineers (IEEE), the National Electrical Manufacturers Association (NEMA), the Society for Automotive Engineers (SAE), Underwriters Laboratory, Inc. (UL), the Scientific Apparatus Makers Association (SAMA), and the Instrument Society of America (ISA).

2.2.1.2 Survey of Documentary Standards

The actual documents produced by the five hierarchies of standards bodies show a great variety both in form and in number. The General Conference of Weights and Measures has issued but three basic documents in fifty years. These documents, however, are the three editions of the International Practical Temperature Scale and they represent the final authority in the field of thermometry. Table 2.2A shows the primary fixed points on the IPTS-68, and the full text is noted in reference 12.

The standards issued by the American Society for Testing and Materials are the product of consensus agreements among manufacturers, users, and objective third parties, as we noted earlier. These standards are issued annually in a multivolume Book of Standards published by ASTM from its offices at 1916 Race Street, Philadelphia, Pennsylvania 19103. Many of these standards are selected by the American National Standards Institute to be designated as American National Standards. Standards so selected are noted in the ASTM listing and the

Table 2.2A

Primary Fixed Points on IPTS-68

State	T_{68} (K)	t_{68} (°C)
thermodynamic zero temperature	0	-273.15
equilibrium hydrogen triple point	13.81	-259.34
equilibrium hydrogen, $p = 33{,}330.6\ N/m^2$	17.042	-256.108
equilibrium hydrogen boiling point	20.28	-252.87
neon boiling point	27.102	-246.048
oxygen triple point	54.361	-218.789
oxygen boiling point	90.188	-182.962
water triple point	273.16	0.01
water boiling point	373.15	100.00
zinc freezing point	692.73	419.58
silver freezing point	1235.08	961.93
gold freezing point	1337.58	1064.43

information which they contain then forms the basis for possible standards consideration by the U.S. National Committees to the International Electrotechnic Commission and to the International Organization for Legal Metrology.

Professional associations are not uniform as regards their issuance of standards. Many of them undertake very few standardization activities, whereas others (for example the National Committee for (Medical) Clinical Laboratory Standards) offer substantial standardization guidance to their members.

The temperature measurement standards issued by government agencies are in the so-called Military Specifications handbooks and in the particular calibration handbooks issued by the individual calibration laboratories, as noted in the previous Section.

2.2.2 Thermometry Instrumentation System

2.2.2.1 Temperature Measurement Tools and Techniques

Many schemes for evaluating temperature have been used since Cro-Magnon yanked his fist out of the fire and grunted at his mate to fetch some cold water. Not so many, however, that we cannot mention some of those in common use today. Galileo's air globe, inverted over a dish of water, was the forerunner of today's gas thermometer, which is probably the most useful of the "thermodynamic" thermometers in the temperature range 20-600 K. These instruments are based on the ideal gas equation $PV = nRT$; commonly either constant-volume or constant-pressure ratios are taken at two temperatures, with the final temperature, T_2, evaluated by the product of the filling, or initial temperature, T_1, and the pressure (or volume) ratio

$T_2 = T_1(P_2/P_1)$ or $T_1 = T_1(V_2/V_1)$.

The trick is to find an ideal gas and to avoid "pitfalls" [20].

Fahrenheit and Celsius developed mercury thermometers, which rely on the different thermal expansion properties of mercury and glass. Although the relative instability of the glass limits their accuracy to 0.01 °C to 0.03 °C, such thermometers enjoy more extensive use today than any other type. This situation is due to their low cost, their simplicity in construction and use, and, for moderate accuracy work, their reliability. These characteristics apply equally well to another commonly used expansivity thermometer, the bimetallic element. These elements ordinarily are bonded strips of nickel steels; at 36% Ni 64% Fe, the alloy has a minimum coefficient of thermal expansion and is called Invar. The alloy containing 18-27% Ni, on the other hand, has a coefficient some twenty times larger, so that the bonded pair forms a sensitive, stable mechanical thermometer capable of 0.03 °C precision in the range 0-100 °C [21].

Similar in principle to the constant-volume gas thermometer is the liquid- or liquid-and-vapor-filled pressure thermometer. In this device a capillary tube connects the sensing bulb to a pressure gauge or to a pressure-sensitive control device. The filled thermometer, although capable of only moderate accuracy, is commonly used because the pressure gauging and control is convenient and reliable.

Resistance thermometry came into common use late in the 19th century with the development of high quality galvanometers. H. L. Callendar developed thermometric elements of platinum wire and derived specifications for evaluating the quality of thermometers [22]. By 1927, much of the ITS could be referred to platinum resistance thermometry, and presently it is possible to obtain measurements of the highest precision from 20 K to perhaps 1300 K by using platinum resistance thermometers [23,24].

In addition to platinum metal resistivity, a variety of other resistive thermometers has become useful over the years. A brief listing of these is included in Appendix E, since some of them will be referred to in later sections.

Thermoelectric thermometry, on which is based the widely used thermocouple, depends on the Seebeck, Peltier, and Thomson effects [25]. The Peltier effect is the liberation or absorption of heat accompanying current flow through the junction of dissimilar metals. The Thomson effect describes the reversible production of heat accompanying the flow of current along a homogeneous conductor whose temperature varies from one point to another. Seebeck's observation that current will flow in a circuit consisting of dissimilar wires connected in a loop in which the junctions have unequal temperatures can be interpreted in terms of the Peltier and Thomson effects. The overall circuit emf can be described by two Peltier coefficients at the junctions and two Thomson coefficients in the two dissimilar wires.

Since its discovery 150 years ago, thermoelectric thermometry has come into extremely wide use. Platinum versus 90% platinum-10% rhodium is the standard interpolating instrument of IPTS from 630 °C-1064 °C, and other thermocouples have been adopted for many temperature measurements and control applications. Table 2.2B shows the ASTM letter designations for thermocouples [26].

Table 2.2B

Thermocouple Characteristics, from ASTM E230-72

Symbol	Elements (+/-)	Useful temperature range
B	Pt-30% Rh/Pt-6% Rh	0 to 1820 °C
E	Ni-10% Cr/constantan	-270 to 1000 °C
J	Fe/constantan	-210 to 1200 °C
K	Ni-10% RH/Ni-5% (Aℓ,Si)	-270 to 1372 °C
R	Pt-13% Rh/Pt	- 50 to 1768 °C
S	Pt-10% RH/Pt	- 50 to 1768 °C
T	Cu/constantan	-270 to 400 PC

By virtue of the radiation given off by a hot object, one can measure its temperature with a radiation pyrometer. The radiation instrument in most common use at present is the disappearing filament optical pyrometer. In its use, the current through a filament is adjusted until its luminance matches that of a glowing object (usually at a wavelength near 650 nm). At that point, the image of the filament blends into that of the object; the filament current control displays the measured temperature.

There are many other methods by which temperature can be measured in particular ranges and with particular accuracies (especially with low accuracy). These methods are listed in Appendix F, since they comprise much of scientific and industrial thermometry. A composite of temperature sensors appropriate for various temperature ranges is given in Table 2.2C.

Table 2.2C

Sensors in Common Use at Various Temperatures

Temperature Range	Sensor	(Approximate) Limiting Accuracy
0-20 K	Semiconductor resistance	±1 mK
20-1000 K	Platinum resistance	± 1 mK (at 20 K) to ±12 mK (at 1000 k)
20-1300 K	Thermocouples	±10 mK (at 20 K) to ±200 mK (at 1300 K)
250-400 K	Mercury-glass	±30 mK
250-400 K	Bimetallic	±30 mK
250-500 K	Thermistor	Uncertain
1000 K	Optical Pyrometer	±0.5 K to 20 K

The IPTS-68 designates the Planck radiation law, the platinum-10% rhodium platinum thermocouple, and the platinum resistance thermometer as the standard interpolating methods for temperatures between the fixed points. These are shown in figure 2.2B, along with other sensors which, while not standard instruments, have come into common use because of a combination of low price and reasonable reliability.

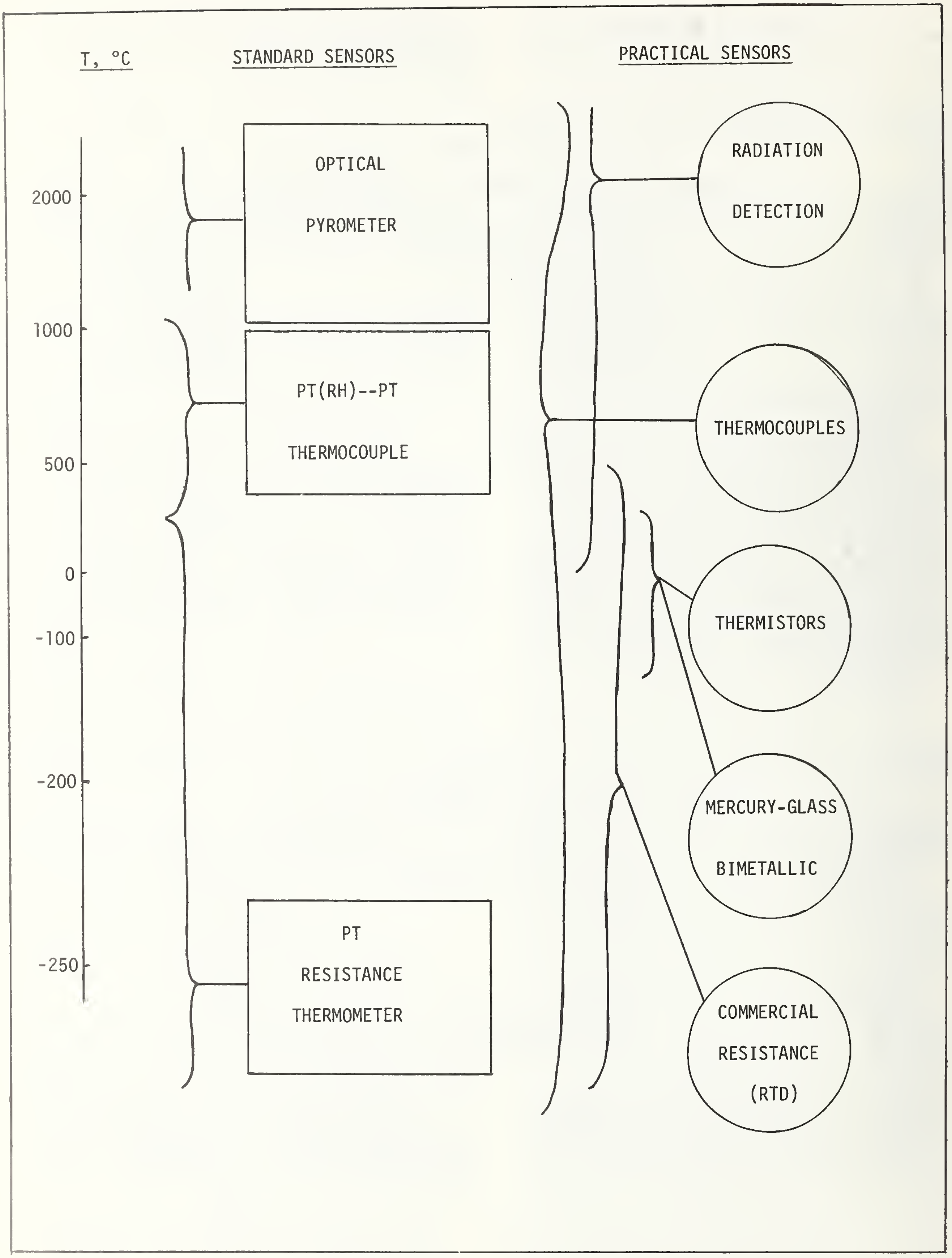

FIGURE 2.2B. Useful Sensor Ranges

As we noted earlier, the triple point of water is of central importance to thermometry; the definition of its temperature as 273.16 K (plus the thermodynamic zero of temperature) sets the "size" of the unit temperature interval, and it thus provides the scale on which the thermodynamic temperatures of all other natural phenomena must be measured. The most common means of realizing the temperature of the triple point of water involves the use of a cell like that shown in figure 2.2C.

The particular cell shown is designed for use with standard platinum resistance thermometers. When the ice mantle is correctly formed around the central tube and the cell is surrounded by a mixture of crushed ice and water, the cell will furnish the triple point temperature very precisely; typically the standard deviation of the platinum thermometer readings at the triple point is less than 0.14 millidegrees.

The simplicity of the triple point of water cell, coupled with its excellent thermometric reproducibility, makes it ideal as the principal defining point for the temperature scale. All but the most modest thermometry facilities can readily incorporate such a cell for ready calibration of temperature sensors.

Although no other fixed point device is quite so easily used as the water triple point cell, many others, especially metal freezing point cells, are in common use. The uses of such cells in thermometry are described in the excellent NBS Monograph 126 "Platinum Resistance Thermometry", by J. L. Riddle, G. T. Furukawa, and H. H. Plumb, from which figure 2.2B was abstracted.

In practice, the sensors described in this section mostly require auxiliary equipment: the optical pyrometer requires, in general, a calibrated lamp or voltage divider; the thermocouple requires a reference junction and, depending on the sensitivity needed for the particular application, either a millivolt - or a microvolt-range meter; and the platinum and other resistance thermometers require Wheatstone or other bridge circuits or an equivalent means (such as a current-potential measurement system) for measuring their resistances. By and large, only the liquid-in-glass and the bimetallic thermometers are free of this need.

As a result of the need for auxiliary equipment, the performance of practical thermometry generally reflects the quality of a *system*, comprising the sensor plus its associated equipment. For this reason, we must concern ourselves to some extent with the products and status of the electronics industry, and we must be careful to take proper account of the influence of the measurement equipment used when considering the reliability of a particular thermometry system.

Much more remains to be said on the subjects of temperature and thermometry than the trifle which comprises Section 2 of this study. However, we have attempted to present here a concise discussion of the scale of temperature as it is derived scientifically and as it is defined in a practical way, and enough information on the evolution and practice of thermometry so that one can appreciate the diversity and vitality of the activities to be described in the balance of the study.

2.2.2.2 The Thermometry Instrumentation Industry

The temperature sensors and associated measuring equipment which form the basis of the thermometry instrumentation industry have been enumerated to a large extent in the preceding Section. In turn, this equipment forms the basis for measurement and control of a very great amount of processing equipment, monitoring equipment, and durable consumer goods--examples of these are the control equipment for the fractionation of petroleum, the temperature monitors on the coolant loop of a nuclear power plant, and the several thermostats in a household cooking range. In this Section, however, we want only to describe the primary thermometry instrumentation industry itself.

This group of people provides the means by which the National Temperature Measurement System makes the bulk of its day-to-day temperature measurements. It includes at least 25 companies with assets greater than $1 million. Very few indeed are the people who construct their own thermometers and temperature control apparatus from scratch (but these few are responsible for nearly all of the advances in the field).

Much routine thermometry is accomplished using thermocouples, (however, resistance thermometry, because of its higher signal-to-noise ratio, is rapidly gaining favor). Many manufacturers provide preassembled couples in various configurations [27], although most people use thermocouple wire provided with the appropriate calibration table to construct simple thermocouple configurations.

The existence of ASTM and other standards for commercial devices will be noted later. These standards are quite effective in promoting uniform quality in thermocouple thermometry since they allow the user to predict the uncertainty in a given temperature measurement, and, usually, in a

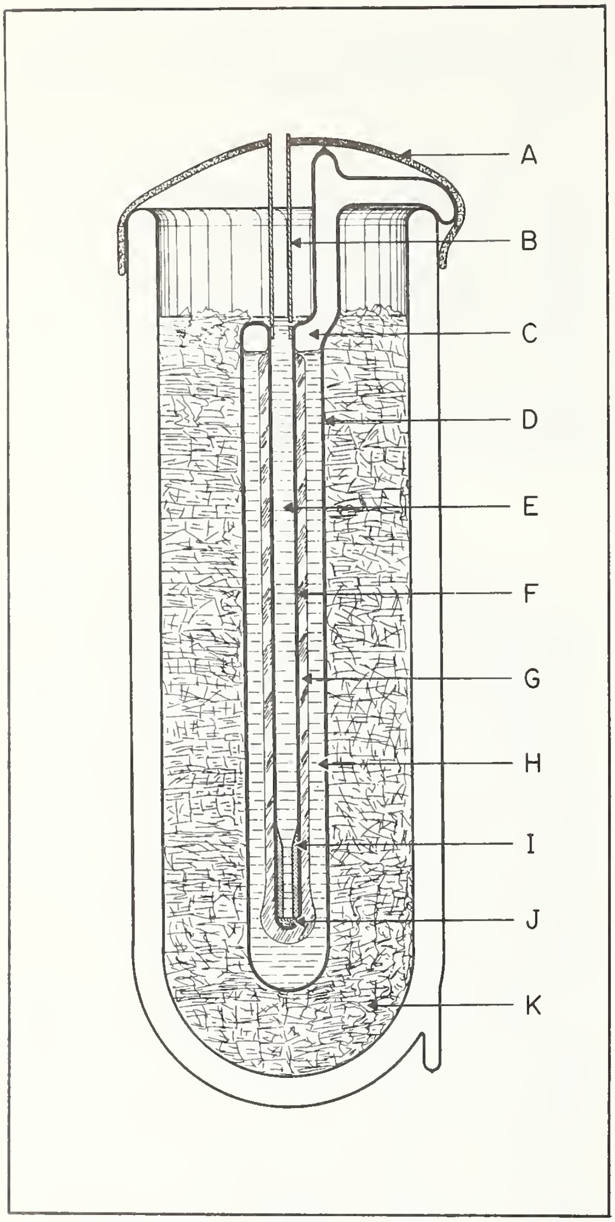

FIGURE 2.2C. Water triple point cell

A. Heavy black felt shield against ambient radiation.
B. Polyethylene tube for guiding the SPRT into the thermometer well.
C. Water vapor.
D. Borosilicate glass cell.
E. Water from ice bath.
F. Thermometer well (precision bore).
G. Ice mantle.
H. Air-free water.
I. Aluminum bushing with internal taper at upper end to guide the SPRT into the close-fitting inner bore.
J. Polyurethane sponge.
K. Finely divided ice and water.

particular control application as well. The great majority of manufacturing processes involving thermocouples require only coarse (perhaps 1%) control of temperature. Typical of such applications are heat treating furnaces; steam, hot water and hot gas plants; and bearing temperature monitoring. The automotive, power generation, metal fabrication, and motor manufacturing industries all employ these applications and use thermocouples in large quantities.

In general, manufacturers of thermocouples and thermocouple wire assure their own conformance to industry standards by using either thermocouples or platinum resistance thermometers which are routinely calibrated at NBS or at a secondary facility. In addition, emf-temperature tables (recently corrected by NBS to conform to IPTS-68) are available for all the common couples.

The construction of automatic reading and recording devices and of temperature control devices for use with thermocouples is a major thermometric industry. Several major companies [28] provide recorders and meters which express common thermocouple outputs directly in temperature units, and these firms also make available control circuitry which will activate heaters, coolers, temperature limit devices, and the like in order to automate processes which involve processing at a particular temperature. The quality control exercised in this industry is often quite thorough, with individual checks on temperature accuracy (in addition to similarly careful checks on mechanical and electrical integrity) using high quality baths and measuring equipment [29]. We have found this industry, taken as a group, to be very conscious of its responsibilities and to be grateful for the active support of NBS through calibration services and consultation.

Bimetallic thermometers, too, are widely used in thermometry and in temperature control applications [30]. One common household thermostat employs two bimetallic thermometers; one for visual indication and the other in the control circuit [31]. Automotive choke and radiator thermostat assemblies also employ bimetallic temperature control units. Calibration of bimetallic units is generally rather coarse, due to the nature of the major applications.

The fastest growing of the temperature sensor industries appears to be the thermistor industry. The thermistor, basically a semiconductor, is finding wide application in the medical area due to its small size and high sensitivity [32]. The same qualities make it a desirable sensor in many other areas, among which are automotive engine temperatures, surface temperatures of manifold systems, micrometeorology, process control, and air conditioning sensing and control. The upper limit for good stability in thermistors is about 300 °C. This industry is made up of many small firms, so that relatively little research has been done to characterize the response, stability, and interchangeability of these sensors. Nevertheless, much automatic reading and control equipment is available for use with thermistors. Some $10-20 million worth of thermistor units are produced in the U.S., and perhaps one-fifth as many are imported from Holland or Germany [33]. Since these units are priced at perhaps 10¢ each but serve much more expensive measuring and control equipment, the thermistor temperature control industry is a large one indeed. Some notion of the rapid progress in the thermistor field can be gained from a recent note [34] that a -5 °C to 45 °C field thermometer system has been developed for use with a voltage-to-frequency converter circuit employing a portable counter.

Another area of rapid growth is in miniature resistance thermometers [35]. The accuracy, sensitivity, and stability of standard platinum resistance thermometers has made them preeminent for exacting thermometry up to 630 °C, and commercial thermometers are now made in many configurations, including some of millimeter dimensions. We have at present limited data [36] on which to judge the extent of any sacrifice in sensor quality resulting from miniaturization or other changes; however, a recent advertisement offers 0.1 °C resolution and ±0.5 °C accuracy (interestingly, the accuracy specification is correctly defined as a "total system" accuracy, a very encouraging sign) [37].

Liquid-in-glass thermometers are widely used for temperature measurement; once filled and calibrated, only column separation and breakage cause obvious changes in the response of these thermometers. Bumping or temperature cycling do, however, cause minute changes in bulb volume which *are* detectable in calibrations. Because of the relative delicacy and expense of control designs based on liquid-in-glass, however, most uses are found in temperature monitoring applications such as batch chemical processing, health care, and household thermometry. There are several large manufacturers of liquid-in-glass thermometers. They sell some $5-6 million worth of ASTM models, as noted earlier, perhaps $7-8 million worth of precision and research thermometers, and roughly the same value in student-group thermometers [38]. The liquid-in-glass units intended for chemical processing and health care are generally calibrated to about ±0.1 °F, and quite often the calibration is traceable to NBS. This is not generally true of the household unit production, however [39].

Optical pyrometers are extensively used in many industries. Subject to inaccuracies owing to uncertain emissivity corrections as well as to differences among particular operators, optical pyrometers still are the thermometers chosen in cases where contact thermometry is especially difficult or where radiation measurements are convenient and reliable, as in surface thermometry.

Many other thermometer sensors are manufactured for particular applications, and control devices are constructed for their employment. Our experience has been that, taken as an industry, thermometer and temperature control equipment manufacturers employ relatively sophisticated personnel and equipment in order to assure the quality of their products in competition with other suppliers of these units. In addition, some of the individual manufacturers support thermometry research and development efforts on a continuing basis. This activity has resulted in the recent development of such advances as cryogenic temperature controllers utilizing semiconductor temperature sensors [40], liquid crystal sensors said to be sensitive to changes of 0.1 °F [41], and radiation sensors which measure temperatures of millimeter-size areas for troubleshooting electronic circuitry [42].

A further measure of the instrumentation industry is found in the Standard Industrial Classification Manual. (See Appendix B). The following codes refer to thermometry:

3822 Measuring and Controlling Instruments
3823 Industrial Instruments for Process Variables
3829 Measuring and Controlling Devices, Other

These codes are further broken down into subcategories for which meaningful economic statistics are gathered by the Bureau of the Census. Representative entries follow: (current Industrial Reports, 1972)

38230 Electrical and Electronic Thermometers, 38 companies with 1972 shipments exceeding $100,000; total shipments $40 million.
38230 Mechanical Thermometers, 40 companies with 1972 shipments exceeding $100,000; total shipments $39 million.
38230 Primary Thermocouples and Leads Wire, 6 companies with 1972 shipments exceeding $100,000; total shipments $11 million.
38230 All other Primary Thermometers, 4 companies with 1972 shipments exceeding $100,000; total shipments $10 million.
38220 Thermostats for heating and cooling,

11 companies with 1972 shipments exceeding $100,000; total shipments $287 million.
38220 Temperature Controls for Appliances, 14 companies with 1972 shipments exceeding $100,000; total shipments $140 million.

The 1973 U.S. Industrial Outlook notes that in 1972 the Automatic Temperature Controls category accounted the following statistics:

$700 million shipments
105 establishments counted
38,000 people employed
4.2% (over $30 million) exported

The outlook projected the shipment level of this category at $1 billion annually by 1980.

Other statistical data could be garnered on the Automatic Temperature Controls category or on other thermometry categories as well. However, we believe that the identification of the sources of such data, together with representative figures showing the enormous volume of activity just in this one facet of thermometry, serves to point up its importance to the U.S. economy.

For the main bulk of industrial shipments, such as those categorized above, the quality of the included thermometric devices is controlled by adherence to American Society for Testing and Materials standards or to similar voluntary or military specifications. In turn, these resistance or thermocouple devices are referred to more accurate standards, and eventually to the NBS. Unfortunately, neither user nor manufacturer is always aware of lapses in which the calibration chain has been broken, with consequent deficiencies in the performance of the equipment.

2.2.3 Reference Data

Much of the most accurate thermometry is preserved on standard thermometers, as we shall see in the next Section. Of the most heavily used thermometry, however, the majority is preserved in the form of reference tables. A notable example of these data is a recent NBS publication, Monograph No. 125 "Thermocouple Reference Tables Based on the IPTS-68". A short discussion of the history of this publication may illuminate the process by which information becomes Reference Data.

In discussions with manufacturers and users of thermocouples and with the corresponding American Society for Testing and Materials committee over a period of years, it became clear that the thermocouple industry relies most heavily on seven types of thermocouple thermometers. With the advent of the International Practical Temperature Scale of 1968, these manufacturer, user, and standards groups suggested (both as groups and in individual correspondence) appropriate temperature ranges and tabular intervals for which reference data for each of the thermocouple types would be most useful. In response to these requests, staff members of the NBS (both in the Temperature Section in the Gaithersburg laboratories and in the Cryogenics Division in Boulder) constructed the new tables of Monograph No. 125. This was accomplished, in some cases, by acquiring new basic calibration data on wire furnished by manufacturers. In other cases, the calibration files were searched for appropriate data which summarized and converted to the new 1968 Temperature Scale. In all cases, computer fitting techniques were used to obtain smooth tabular values of thermocouple e.m.f. versus temperature.

These particular thermocouple reference tables are sold to the public both in the U.S. and abroad through the U.S. Government Printing Office. In an effort to avoid "going out of print" in less than five years, the Printing Office ran off 20,000 copies in the first printing.

Monograph 125 is now in use by thermocouple wire manufacturers, whose Quality Control laboratories run continuing calibration checks to ascertain that the wire as manufactured does yield the tabulated emf versus temperature within limits specified by the appropriate manufacturing standard. The instrumentation industry also uses Monograph 125 to determine that meter outputs (often given directly in temperature) correspond to the tabulated values. (We might note here that this industry specifically requested that a supplement to Monograph 125 be issued with the tabular temperatures on the Fahrenheit Scale, for those of their customers not yet able to use the metric Celsius scale. NBS complied with this request within one year.) Major users of thermocouples use Monograph 125 in the calibration of thermocouples employed in test stands, process control instrumentation, and materials data evaluation.

Thus we see, in the history of one document, the manner in which a technical need is observed and answered by the NBS staff in generating Reference Data in thermometry.

Similar Reference Data are now in the process of being obtained at NBS for small, commercial thermistor and resistance thermometers. Some data obtained by various industrial representatives are in existence but their value is restricted since the interchangeability, stability and accuracy limitations of the corresponding sensors are not generally available or not known. Such data, when available, will play a role similar to that of Monograph 125.

Hardly data in the usual sense of the word, the Reference Functions of the 1968 International Practical Temperature Scale nonetheless constitute a primary source which are used in the interpolation of the temperature scale between fixed points of temperature information. These functions are found in the journal Metrologia *5* 35 (1969); they are employed with the capsule standard platinum resistance thermometer to obtain values of temperature in the range 13.81 K to 273.15 K.

2.2.4 Thermometry Reference Materials

The primary reference materials of thermometry comprise the pure materials used in fixed-point devices and in thermometers. For example, NBS Special Publication 260 lists two Standard Reference Materials, high-purity zinc and tin, which are suitable for use in the construction of freezing-point cells. These cells, properly prepared and used, may then serve to define calibration temperatures on the International Practical Temperature Scale of 1968 [43]. The high-purity platinum wire which is used in constructing standard resistance thermometers also constitutes a thermometry reference material. Similarly, the thermoelectric standard Pt 67, soon to be designated as a Standard Reference Material by NBS, is a valuable reference material in thermometry.

In one case, a fixed-point device may be considered to comprise a thermometry reference material. This is the Superconductive Thermometric Fixed Point Device, which has been designated by NBS as Standard Reference Material 767—when the device leads are connected to a simple measuring circuit, the user may rely on the thermometric reproducibility of the included superconductive samples [44].

Somewhat less accurate thermometry reference materials are under development in the Physical Chemistry Division of NBS [45]. These are standards for differential thermal analysis.

Many scientific and industrial laboratories maintain "old faithful" materials which they employ as thermometry reference materials. Often, however, these materials are of uncertain purity or are known to be impure, so that they enjoy only a very local usefulness. A value of the NBS Standard Reference Material program lies in the fact that their products, being generally of very high purity and careful characterization, can be readily duplicated. Thus their thermometric properties can be utilized throughout the Measurement System.

2.2.5 Science and People

In considering the National Temperature Measurement System infrastructure, one must first realize that temperature is not of direct interest to most people who measure it. For the most part, people who measure temperature want to obtain a reproducible, readily interpretable result for a clinical laboratory blood test, or they want to ensure that a batch of steel, semiconductors, or plastic meets its specifications, or they want to optimize the efficiency of a steam boiler, of a turbine, or of a chemical process.

It is true that many people are interested in the specific temperatures at which various physical and chemical phenomena take place, and occasionally they relate these temperatures to theoretical derivations; in addition the temperature measurement industry is directly interested in temperature *per se*. On balance, however, the less concerned the average person has to be with the measurement process and the thermometry system he is using, the happier he is. For this reason, the primary objective of thermometricians and of thermometry equipment manufacturers is to make temperature measurement as accurate, as automatic, and as efficient as they can.

The sciences of Physics and Chemistry both underlie thermometry--rather, one might better note that thermometry underlies both of these fields and most of the engineering sciences as well! Many of the fundamental advances in thermometry have arisen as scientists reached for new tools with which they could probe the mysteries of nature, and it is still true that most professional thermometrists have accompanying interests in one of a variety of scientific areas.

The scientific underpinning of thermometry is to be found in a great kaleidoscope of scientific and technical societies and their journals. The principal publications are Metrologia, the international journal of metrology, the Review of Scientific Instruments, the Physical Review, and the Journal of Chemical Physics. Corresponding to these in technical areas are journals such as Instrumentation Technology and the NBS Monograph series. The American Institute of Physics and its member societies, the Instrument Society of America, and a wealth of scientific and engineering organizations contribute personnel to the study of thermometry.

2.3 Realized Thermometry Measurement Capabilities

The ease with which precise and accurate temperature measurement can be provided varies considerably with the temperature range and with the application of the user.

The most-used range of temperature is the range 0-200 °C; this is where most human activities take place. The reader will appreciate that these activities involve far and away the most numerous measurements of temperature of any part of the national system. However, the "quality" of thermometry required in these activities is, for the most part, adequately met by the cheapest and least accurate sensors available—the humble mercury-in-glass and bimetallic thermometers and the thermocouple. Offering accuracies of one degree or so and precisions of perhaps one-tenth degree, these are the counterpart of the "dollar watch"—cheap but adequate.

There is an aspect of each of the items in the preceding paragraph to which the free-and-easy remarks made there do not apply. This aspect is that of the professional in each of the areas named. It is true that we can live and work effectively in buildings whose temperatures vary substantially from the norm; however, the professional building designer can do his job correctly only with the benefit of thermometry which is much more precise than our own requirements. The same is true of the automotive designer, of appliance manufacturers, and of the medical profession.

The many different applications of temperature measurement means that a great deal of effort is involved in getting a comprehensive overview of the needs for temperature precision and accuracy.

The major aspects of thermometry capabilities have been noted already. They appear in summary form in Tables 2.2B and 2.2C and in figure 2.2B.

2.4 Thermometry Dissemination and Enforcement Network

The network of standardization institutions has already been examined in Section 2.2.1. Here we shall note the dissemination and enforcement institutions.

2.4.1 Central Thermometry Standards Authorities

a) International organizations concerned with thermometry--The General Conference on Weights and Measures, including its component bodies (the International Committee for Weights and Measures, the International Bureau of Weights and Measures, the Advisory Committee on Thermometry, and its Working Groups). This body is responsible for the construction and promulgation of the International Practical Temperature Scale.

Arising from the treaty of the Meter, a 17-nation convention meeting in Paris in 1875, were a General Conference on Weights and Measures, an International Committee on Weights and Measures, and an International Bureau of Weights and Measures [46]. The General Conference meets at six-year intervals, when it considers agenda items which are introduced by one or more Advisory Committees, including (since 1937) an Advisory Committee on Thermometry (le Comité Consultatif de Thermométrie, or C.C.T.).

Table 2.4A shows a sketch of the General Conference structure:

Table 2.4A

General Conference on Weights and Measures

41 Nations subscribe, Conference meets at about six-year intervals - 14th meeting was October 1971.

International Committee on Weights and Measures

18 Nations, elected by the General Conference; it is the executive body; meets at two-year intervals at BIPM.

Advisory Committee on Thermometry

12 Major National Standards Laboratories and some six individual advisors; 10th Session was May, 1974 at BIPM. USNBS Representative at 10th Session
R. P. Hudson, Division 221
H. H. Plumb, Temperature Section

Its Missions are:
1. Recommend scale improvement based on working group observations.
2. Study thermometric techniques.

International Bureau of Weights and Measures

Paris, Parc de St. Cloud.

Its missions are:
1. Fundamental scale research.
2. International scale comparisons.
3. Coordination of measurement techniques.
4. Coordination of physical constants measurements.

Working Group 1: Preston-Thomas, NPL, NBS (H. H. Plumb), IMM; Revisions of IPTS-68
Working Group 2: IMGC, CNAM, NRC; secondary fixed points, simplified techniques
Working Group 3: NPL, PTB, NBS (L. A. Guildner); Thermodynamic Temperatures above 100 K
Working Group 4: KOL, Swenson, NSL, IMPR; Thermodynamic Temperatures below 100 K
Working Group 5: NBS (R. P. Hudson), Japan, NPL; Practical Thermometry Below 30 K

As can readily be seen by a glance at Table 2.4A, the thermometry work of the General Conference and its subsidiary organizations is the definition of the thermodynamic scale and the promulgation of an International Practical Scale as closely duplicating thermodynamic temperatures as can be accomplished within the limit of practical utility. Within the United States, the National Bureau of Standards is responsible for coordinating this effort. Much of the actual scale work is done at the NBS, so that such efforts constitute a substantial part of the NBS thermometry.

A second international standards authority is the International Organization for Legal Metrology and its component bodies (the International Bureau for Legal Metrology, the International Committee for Legal Metrology, and its Secretariats, Technical Committees, and Working Groups). The OIML issues International Recommendations on technical data and instruments which are the concerns of Legal Metrology in member countries. See Section 2.2.1.

b) U.S. Thermometry Authorities

National Bureau of Standards. The NBS provides temperature calibrations based on the International Practical Temperature Scale of 1968, and it provides consultative services in thermometry to science, to industry, and to standards institutions at all levels.

c) Other National Authorities

Many nations maintain primary standards laboratories, some of which are also legal metrological institutions. Among the more prominent national standards laboratories are those of England, Canada, Australia, France, Germany, Japan, Russia, Italy, and The Netherlands.

2.4.2 State and Local Offices of Weights and Measures

The state offices of weights and measures for the most part are inactive in thermometry. Exceptions to this rule are the states of Connecticut, Massachusetts, and Michigan. These are "Seal States" (any thermometers sold in the state must have the approval of the State Office of Weights and Measures). The offices in these states maintain calibration laboratories and examine a great many thermometers each year.

2.4.3 Temperature Standards and Testing Laboratories and Services

The principal thermometry standards laboratories (apart from those described elsewhere) exist in Federal agancies, in industrial instrumentation and manufacturing concerns, and, in a few cases, in commercial testing laboratories.

Some of the most prominent of these are:

- Department of Defense calibration centers, strategically located to serve the Navy, Army, or Air Force needs
- Energy Research and Development Administration laboratories at Sandia Laboratories, Savannah River and Oak Ridge National Laboratory
- National Aeronautics and Space Administration laboratories at Huntsville, Alabama and at Orlando, Florida
- Standards and calibration laboratories maintained by major thermometry instrument manufacturers and major users of thermometry.

a) Government and Commercial Temperature-Calibration Facilities

A great many facilities exist for the calibration of thermometers and other standard instruments. Of special interest are facilities run by various government agencies for the calibration of their own and their contractors' instruments, and commercial facilities which calibrate instruments for all comers on a fee basis.

We have examined in some depth the system of calibration laboratories operated by the U.S. Navy. This system is shown schematically in figure 2.4A. NBS calibrates instruments which are used in the primary or Type I standards laboratories to calibrate periodically all the secondary (Type II) laboratory standards. In turn, these are used to calibrate the 300-odd "calibration" facilities which serve the Navy's own and its contractors' needs.

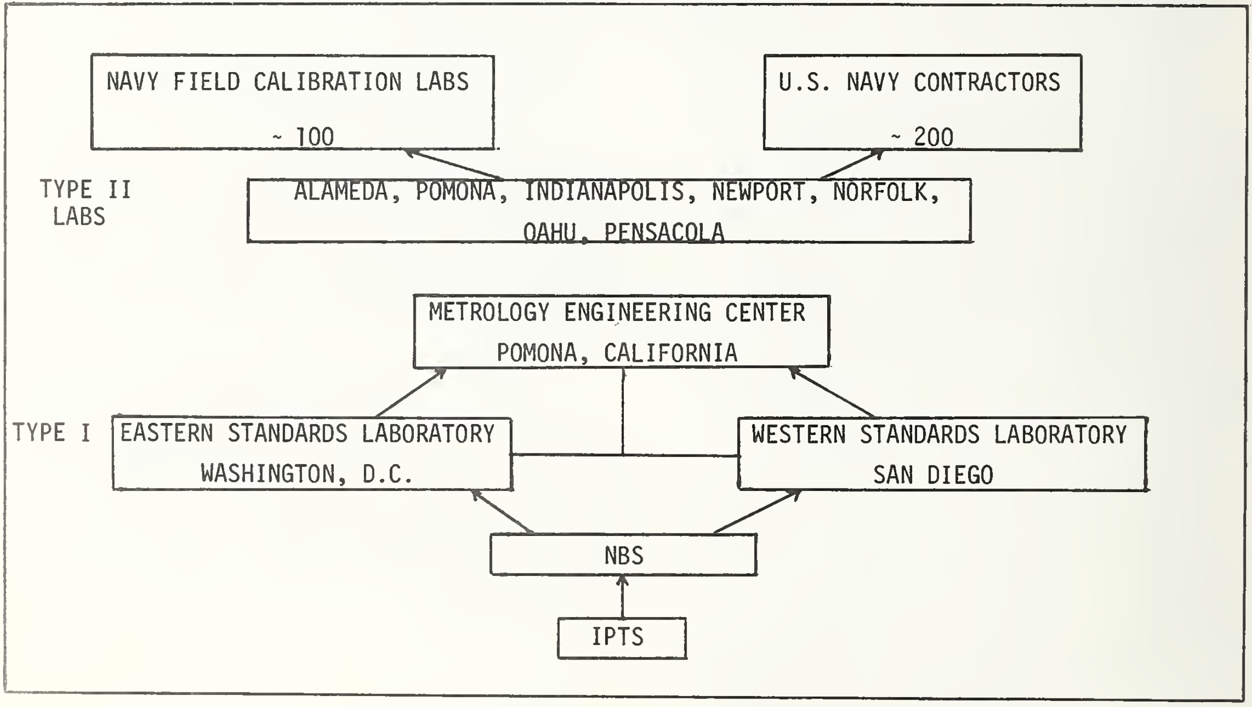

FIGURE 2.4A. U.S. Navy Temperature Calibration Chain.

The Army, as well, has a highly developed calibration system. The calibration laboratory at Redstone is the Army Standards Laboratory and it represents the highest level (primary reference) of calibration standards capability within the Army and provides primary certification service for Army calibration activities in the Continental United States (CONUS) and for the Army Calibration Laboratories overseas. Army Calibration Laboratories provide CONUS calibration service within designated geographical areas: Anniston Army Depot, Alabama; Letterkenny Army Depot, Pennsylvania; Lexington-Blue Grass Army Depot, Kentucky; Pueblo Army Depot, Colorado; Sacramento Army Depot, California; Tobyhanna Army Depot, Pennsylvania; and Tooele Army Depot, Utah.

The Redstone temperature facility is directly dependent upon NBS. The following discussion is taken from reference 47, p. 99:

"Standard

"NBS traceability is maintained by a group of Myers type platinum resistance thermometers which are periodically calibrated by NBS. Working standards are regularly checked against triple point of water cells (.01 °C) to insure that the measurement system is not drifting.

"Techniques

"Platinum resistance thermometer (PRT) certifications are performed by taking measurements at the triple point of water (.01 °C), the freezing point of tin (231.97 °C), and the freezing point of zinc (419.58 °C). The resistance of the thermometer at each temperature is determined with a G-4 Mueller Temperature Bridge having resolution to 1 micro-ohm.

"Platinum-platinum 10% rhodium thermocouples are certified by taking measurements at the freezing point of anitmony (630.7 °C), the freezing point of silver (961.9 °C), and the freezing point of gold 1064.4 °C). Measurements are referenced to the ice point and voltages are determined with a potentiometer having resolution to .01 microvolt. The freezing points of tin, lead, zinc, aluminum, and copper are also available for the calibration of thermocouples.

"Cryogenic temperature sensors are certified by comparison with a platinum resistance thermometer in a stirred bath. Bath media range from ethylene glycol (-40 °C) to salt (500 °C)".

The range and accuracy of various Army thermometry capabilities are shown in Table 2.4B [48].

Table 2.4B

Temperature

Range and Accuracies

Item/Parameter	Range Conventional	S.I. Unit	Accuracy (±) Conventional	S.I. Unit
Liquid in Glass Thermometer	-38 to 500 °C	235 to 773 °K	0.01 °C	0.01 °K
Differential Hz in Glass Thermometer	0 to 100 °C	273 to 373 °K	0.005 °C	0.005 °K
Platinum Resistance Thermometer	-40 to 500 °C	90 to 773 °K	0.002 °C	0.002 °K
Thermocouple	-40 to 1450 °C	233 to 1723 °K	0.25% for Pt-Pt Rd to 1300 °C or 4 microvolts	0.25% for Pt-Pt Rd to 1573 °K
Black Body Radiation Source Temperature		(see thermocouple data)		
Cryogenic Thermometer	-269 to -181 °C	4 to 92 °K	0.03 °C	0.03 °K

Similar calibration operations are maintained by the U.S. Air Force, by the USAEC, and by NASA. Of course, the question of whether all of these government calibration facilities actually maintain the levels of accuracy to which they aspire can only be settled by Measurement Assurance Programs (MAP) of the sort that are now in progress with Sandia Laboratory, Redstone Arsenal, Leeds and Northrup, and others. Even more difficult to answer are the questions of whether the stated levels of accuracy are required by the needs of the using organizations, and whether they actually obtain the accuracy they need.

The National Conference of Standards Laboratories has prepared a useful Directory of Standards Laboratories [49] which lists commercial facilities offering temperature calibrations for a fee. Table 2.4C contains a listing of these companies.

Table 2.4C

NCSL Listing of Commercial Calibration Facilities

	Primary	Secondary
Aerojet Electro Systems Company	X	X
Allis Chalmers Manufacturing Company	X	X
American Geophysical and Instrument Company, Inc.	X	X
AVCO-Lycoming		X
AVCO Corporation	X	X
Bendix Corporation	X	
Boeing Aerospace	X	X
Boeing Wichita	X	X
Burroughs Corporation	X	X
Cannon Instrument Company	X	
Colorado Engineering Expt. Station	X	X
E.G. and G., Inc.		X
Electro-Scientific Industry, Inc.	X	X
John Fluke Manufacturing Company		X
General Dynamics Corporation	X	X
General Electric Company		X
Hercules, Inc.		X
Hewlett Packard Company	X	X
Honeywell	X	X
ITT Research Inst.	X	X
Leeds and Northrup	X	X
Clifton (Litton Ind.)		X
Lockheed-California Company	X	X
LTI Research Foundation		X
LTV Electrosystems, Inc.	X	X
McDonnell Douglas Astronautics	X	X
Martin Marietta Corporation	X	X
National AstroLabs/Metrolonies		X
North American Rockwell	X	X
NAR, Rocket Dyne Division		X
Sanders Associates, Inc.	X	
Singer General Precision, Inc.		X
Sperry Electronic Tube Division	X	
SSCO Standards Lab	X	
Teledyne McCormick Selph		X
Teledyne Systems Company	X	X
TRW Systems Group	X	X
Tucker Electronics Company		X
Varian Associates		X
Volumetrics	X	X
Westinghouse Electric Company	X	X

The purpose of displaying this list is to show the extent of calibration activities. NBS has contact with this group primarily through its calibration services and MAP activities. The latter determine actual scale transferral accuracy and represents a large undertaking.

2.4.4 Regulatory Agencies

The principal Federal regulatory agency which is involved heavily in thermometry is the Food and Drug Administration. This agency, like the three "Seal State" Weights and Measures offices, has the responsibility for regulating the sale of medical electronic thermometers and for the thermometric aspects of health instrumentation.

The nature of the activities of the regulatory agencies often demands rather quick decisions on the safety or reliability of a given product. Because of this problem, these agencies occasionally request information which is difficult for NBS to supply on a short-term basis. A recent case in point is that of medical electronic thermometers, which come under the purview of FDA; to evaluate the quality of particular instruments (let alone the evaluation of the quality of the manufacturing, which was the information actually desired) appeared to require a substantial amount of time, if NBS were to conduct an orderly, statistical investigation. Yet FDA felt constrained to quickly address the question of the reliability of these thermometers, since the public safety was involved. Similar situations, of course, can be expected to recur in this and other areas, and the problem offers a challenge to NBS to aid these agencies effectively.

As de facto regulatory agencies, the College of American Pathologists and the American Hospital Association participate in the accreditation of hospitals through the certification of the quality of their thermometry capability. By and large, this certification procedure comes down to evidence of treaceability to the NBS.

2.5 Direct Measurements Transactions Matrix for Thermometry

2.5.1 Analysis of Thermometry Suppliers and Users

In order to attempt a codification, or evaluation of the thermometry activities of the U.S. in summary form, it is necessary to categorize the various components--as indeed we have done in the preceding Sections.

For the purposes of this Section, we shall tabulate fifteen sectors of the thermometry community in an order which is common to all portions of the NBS Measurement System study. In this Table 2.5A are listed representative entries, their principal roles as *suppliers* of thermometric sensors, instruments, data, or information, and all the corresponding roles as *users*. We have also indicated, where appropriate, Standard Industrial Classification codes which apply to these entries.

In addition to Table 2.5A, describing the various supplier and user roles in the National Temperature Measurement System, we have attempted to construct a matrix describing the transactions which occur between supplier and user groups. In this Direct Measurements Transactions Matrix, Table 2.5B, groups described in Table 2.5A are listed in columns 1-25 in their roles as users of thermometry, and in rows 1-25 as suppliers. The code to the entries is as follows:

A. In the center of each matrix element, the numbers indicate the magnitude of the activity between supplier and user

None - trivial
1 - minor
2 - moderate
3 - important
4 - major

B. In the lower left corner, any change in the activity level is shown.

N - declining
0 - stable
2 - growing
4 - growing explosively

C. In the upper left corner, the level of importance of the activity is indicated

1 - purely convenience
2 - strongly desirable
3 - no real alternative
4 - essential.

D. In the upper right corner, the adequacy of the activity is indicated.

0 - entirely adequate
1 - could be improved
2 - marginal
3 - serious deficiencies
4 - really unsatisfactory

E. In the lower right, the primary type of thermometry activity supplied is coded according to the letter equivalents in Table 2.5A.

2.5.2 Highlights of Thermometry Users

The major users of thermometry, as might be expected, are the manufacturing concerns of categories (4) and (14), although all of the categories listed in Table 2.5A use two or more of the letter-coded thermometry goods and services.

The number of classes of such thermometry users is so large, as we noted in the introduction to this study, that we can scarcely hope to list them, let alone discuss their individual needs. Let us rather submit that in the general case, their requirements for accuracy and precision are not high and are adequately met by available thermometry.

Ultimately, of course, even the drug store thermometer manufacturer relies on NBS for the integrity of his product. One such supplier referred to NBS as "the heart of (his business). We could not function without NBS" [50]. The reason that this is so is that both voluntary standards and most legal requirements refer specifically to NBS as the final authority in matters of temperature. This situation leads to a continuing need for NBS to maintain calibration services for the various sensors and ranges in common use.

Besides its role as an "invisible" partner in much of our daily lives, temperature figures more prominently in many other areas. It is the life-blood of the temperature controls industry, of course, and it plays a strong role in the broader classifications of general controls and of precision instrumentation through the frequent presence of temperature stability or temperature regulation requirements. The petroleum industry is the biggest single user of liquid-in-glass thermometers, whose sales volume is $5-6 million in ASTM-specified models alone. The chemicals industry, steel and automotive equipment manufacturing (in fact, the general class of manufacturing) all feature multitudes of carefully-maintained standards and quality control laboratories which uniformly include temperature standards. Power companies; the aerospace industry; the Department of

Table 2.5A

The Thermometry Community and Its Roles as Suppliers and Users of Thermometric Goods and Services

Key to Supplier/User Entries
A - Thermometric Reference Data and Compilations of Such Data
B - Temperature Calibrations
C - Temperature Sensors and Associated Instruments
D - Thermometric Instruction and Consultation
E - "Thermometry Needs" Information
F - New Thermometry Methods
G - Thermometry Texts and Literature
H - Temperature Control Devices
J - Temperature Standards and Regulations
K - Money for Thermometric Research and Development
L - Durable Goods Incorporating Temperature Control

	Sector	Supplies		Uses	
(1)	The Knowledge Community Scientific Organizations Academic Institutions Professional Societies Technical Publishers SIC Codes: 2721, 2731, 2741, 7391, 8071, 8221, 8231, 8911, 8922, 8999	A E G	D F	A C F H L	B D G K
(2)	International Metrological Organizations General Conference of Weights and Measures; Standards Laboratories of England, France, Australia, Holland, Italy, Japan, USSR, Canada	A D H	B F J	A C F H K	B E G J L
(3)	Documentary Specification Organizations International Electrotechnical Commission, International Organization for Legal Metrology, American National Standards Institute, American Society for Testing and Materials, Department of Defense Military Specification Activities	A J		A	D
(4)	The Instrumentation Industry Manufacturers of temperature sensors measurement equipment, temperature control equipment SIC Codes: 3822, 3823, 3829	B D F H	C E G	A C E G K	B D F H L
(5)	National Bureau of Standards Plant Division, Instrument Shops Division, Electricity Division, Mechanics Division, Heat Division, Optical Physics Division Cryogenics Division, Electromagnetics Division, Time and Frequency Division, Analytical Chemistry Division, Polymers Division, Metallurgy Division, Inorganic Materials Division, Reactor Radiation Division, Physical Chemistry Division, Engineering and Product Standards Division, Electronic Technology Division, Center for Building Technology, Center for Fire Research SIC Codes: 8922	A D F K	B E G	A C E G J L	B D F H K

Table 2.5A (Continued)

	Sector	Supplies		Uses	
(6)	Other U.S. National Standards Authorities This is a null entry for thermometry.				
(7)	State and Local Offices of Weights and Measures	J		A C J	B D
(8)	Standards and Testing Laboratories Army, Navy, Air Force, National Aeronautics and Space Administration, Energy Research and Development Administration, Major Instrument and User Corporations Calibration Laboratories SIC Codes: 9611, 9661, 9711	B	D	A C G J	B D H
(9)	Regulatory Agencies U.S. Food and Drug Administration, College of American Pathologists, American Hospital Association SIC Codes: 9431	J	K	A C G	B D
(10)	U.S. Department of Defense (except Certification and Calibration Laboratories) SIC codes: 9711	E K	F	A C F H K	B D G J L
(11)	Other Government Agencies (except Calibration Laboratories) Energy Research and Development Administration, National Aeronautics and Space Administration, Health, Education and Welfare Department, Department of Commerce, United States Department of Agriculture, Interior Department, Housing and Urban Development SIC Codes: 9531, 9532, 9661	E K	F	A C F H K	B D G J L
(12)	State and Local Government (except Offices of Weights and Measures Essentially a null entry			C H	D L
(13)	Industrial Trade Associations Scientific Apparatus Makers' Association, Instrument Society of America, Society for Automotive Engineers, National Electrical Manufacture Association, etc. SIC Code: 8911	E		D	J
(14)	Intermediate Industrial Users or Suppliers Manufacturers of durable goods of all types (e.g., laboratory furnaces, household ranges, washers, dryers, air conditioners, airplanes, automobiles and parts); manufacturers of chemicals, plastics, fertilizers, etc.; mining and petroleum companies; transportation companies; industrial and household repair companies; (and many others)	D F K	E H L	A C E G J L	B D F H K

Table 2.5A (Continued)

	Sector	Supplies	Uses
(14)	(Continued)		
	SIC Codes: Truly too numerous to list!		
(15)	General Public Each of us as individuals rather than as employees of a particular organization	E	C D G H L

Defense, State Weights and Measures Bureaus and other governmental agencies all need to measure temperature to a greater or lesser accuracy. For many of these portions of the NMS, temperature is an important parameter which helps govern whether an instrument, a process, or a product will meet specified criteria, and the thermometric activity amounts to using a well-known sensor in a standard way to ensure adequate results. In other cases, primarily research and development activities, a stable sensor does not exist, and the problem is avoided by widening tolerances or the group involved becomes a (probably unwilling) party to thermometric research.

The group of customers for temperature instrumentation is so broad as to be apparently of little value as a subject for discussion--if the reader considers the heading for a moment, he will realize that just about everybody belongs to it. The automotive manufacturing industry, power manufacturers, and the petroleum, plastics, chemicals, glass, aerospace, electrical appliance, and electronics industries are using temperature as a process parameter. In answer to the obvious question, we hasten to observe that an important characteristic is shared within this group. This characteristic is an attitude toward temperature measurement as a necessity to be subdued as painlessly as possible. Of course, the quality of thermometry which is accomplished by members of this group varies widely, and our feeling, based upon conversations with many individuals, is that this quality depends very strongly on the equipment and information which is at hand. In the case of corporate activities, especially, cost considerations also play a large part in determining the nature of such "incidental" thermometry.

The significance of this perhaps obvious observation is that any activity which raises the level of awareness of the utility and availability of adequate thermometry, or which raises the quality of thermometry available at a given cost, will have far-reaching effects simply because of the great numbers of people involved.

Even among such an erudite group as research scientists (and we do not exclude NBS!), individuals occasionally *unnecessarily* degrade the quality of their research by failure to apply careful thermometric (or other standard) techniques. Corporate examples can be chosen almost at will from the ranks of manufacturers of all kinds of commodities; two such examples might illustrate the nature of the problem: in one case an experimental laboratory in the automotive industry only now (and with nonprofessionally trained personnel) is attempting to base engine design upon temperature and pressure profiles; in another, a major power producer expressed *no concern* that uncertainty in temperature measurement might well be decreasing the thermodynamic operating efficiency by several percent, thus wasting dwindling fuel supplies.

Balancing these examples, of course, are others in which thermometry development is underway to enhance the quality of a product--one corporation, for example, is studying the miniature platinum resistance thermometer in order to improve its differential thermal analyzer [51], and a large computer firm is active in thermometry in order to make its semiconductor manufacturing more efficient, requiring ±1 °C for 16 hours at 1200 °C [52]. Nonetheless, it would appear that effective work in this area by NBS will be very productive in terms of increased quality of thermometry.

The opportunities for NBS to make contributions in this area are varied and economically impressive. To cite a few examples, a major film maker reported a need for temperature reproducibility at the ten millidegree level and a desire for stability at the one millidegree level from 0-65 °C, both presently beyond their capability [53]; a kiln requires, for optimum output, continuous monitoring of an air atmosphere within 5 °F at 1800 °F, again beyond its present capability [54]; most flow measurements require temperature calibration, for accuracy as well as for subsidiary pollution

DIRECT MEASUREMENTS TRANSACTIONS MATRIX FOR USERS SUPPLIERS	KNOWLEDGE COMMUNITY (Science, Educ., Prof. Soc. & Publ.) 1	INTERNATIONAL METROLOGICAL ORGANIZATIONS 2	DOCUMENTARY STANDARDS ORGANIZATIONS 3	INSTRUMENTATION INDUSTRY (SIC Major Gp 38) 4	NBS 5	OTHER U.S. NATIONAL STANDARDS AUTHORITIES 6	STATE & LOCAL OFFICES OF WEIGHTS & MEASURES 7	STANDARDS & TESTING LABORATORIES AND SERVICES 8	REGULATORY AGENCIES (excl. OWM's) 9	DEPARTMENT OF DEFENSE (excl. Stds. Labs) 10	CIVILIAN FEDERAL GOVERNMENT AGENCIES 11	STATE AND LOCAL GOVERNMENT AGENCIES 12	INDUSTRIAL TRADE ASSOCIATIONS 13	INDUSTRIAL MANUFACTURING 14	HEALTH SERVICES (SIC Major Gp 80) 15	GENERAL PUBLIC 16
1 KNOWLEDGE COMMUNITY (Science, Educ., Prof. Soc. & Publ.)	2 4 A	2 2 A	1	1 3 D	2 3 A					1 3 D	1 3 D				2 3 2 2 [illegible]	1 1 2 G
2 INTERNATIONAL METROLOGICAL ORGANIZATIONS	3 2 A	3 3 A	1 1 A		3 3 F								1 1 A		2 1 3 2 J	
3 DOCUMENTARY STANDARDIZATION ORGANIZATIONS	1		3 3 3 2 J	2 1 4 2 A	1 1 1 2 E		?			1	1		1 1 1 2 E		1	1
4 INSTRUMENTATION INDUSTRY (SIC Major Gp 38)	2 1 3 2 C	2 1 2 2 C	4 3 2 D	4 1 4 2 H	3 1 4 2 C		?	2 1 3 2 C	2 1 2 2 H	4 1 4 2 H	4 1 4 2 H	2 1 2 2 C	4 1 3 2 D	4 1 3 2 C	4 3 4 4 C	4 3 4 2
5 NBS	3 3 3 A	4 2 4 2 A	2 1 3 2 D	2 3 3 2 A	2 3 3 2 A		2 2 1 2 B	2 3 3 2 A	2 3 2 2 A	2 3 3 D	2 3 3 D		2 1 2 2 D	2 1 2 2 D	2 1 3 2 D	1 1 1
6 OTHER U.S. NATIONAL STANDARDS AUTHORITIES																
7 STATE & LOCAL OFFICES OF WEIGHTS & MEASURES					1 1 1 2 E		1 1 D		?			1 1 1 2 D		1 2 1 2 J	1 2 1 2 J	1 2 1 2 J
8 STANDARDS & TESTING LABORATORIES AND SERVICES			2 2 D	2 3 E	2 2 E			3 2 4 2 B		3 2 3 B	3 2 2 B			1	1	
9 REGULATORY AGENCIES (excl. OWM's)					2 4 1 2 E				1 4 1 ? J			?		3 1 1 2 J	3 1 2 2 J	4 3 2 2 J
10 DEPARTMENT OF DEFENSE (excl. Stds. Labs)			1	2	1 1 1 K			2 1 3 2 E		4					1	
11 CIVILIAN FEDERAL GOVERNMENT AGENCIES	1		1	2	2 1 2 E			1			1 2 3 D	2		1 3 D	1	
12 STATE & LOCAL GOVERNMENT AGENCIES				1								1				
13 INDUSTRIAL TRADE ASSOCIATIONS	1 1 A		2 2 E	1 E	2 1 E	2		?			?		2 1 1 D	1 1 E		2 1 1 A
14 INDUSTRIAL MANUFACTURERS			3 1 3 E	3 2 3 2 E	3 3 3 2 E		2 1 1 E	2 1 1 E	2 1 1 E	2 1 2 E	2 1 2 E	2 1 1 E	2 1 2 E	3 1 4 A		2 3 2
15 HEALTH SERVICES (SIC Major Gp 80)		2 1 1 E	2 1 1 E	2 3 3 2 E	2 1 3 2 E		1		2 1 1 E						3 1 4 D	4 3 4 2
16 GENERAL PUBLIC				2 3 2 2	1				2 1 2 2		2					3 1 4 D

Key to Matrix Entries

C - Importance of Transactions

1 - Purely convenience
2 - Strongly desirable
3 - No real alternatives
4 - Essential

D - (In)adequacy of Services

0 - No improvements needed
1 - Could be improved
2 - Marginal
3 - Serious deficiencies
4 - Out of control

C D
A
B E

B - Rate of Change

N - Declining
0 - Stable
2 - Growing
4 - Growing Explosively

E - Thermometry Services Supplied

See Table 2.5A
? - Unknown
X - Not studied
Blank = 0

A - Magnitude of Transactions

0 - Trivial
1 - Minor
2 - Moderate
3 - Important
4 - Major

measurements, and this is simply not available; National Marine Fisheries Service, of NOAA, has found that a fraction of a degree change in water temperature can "radically alter" the feeding habits of tuna. This finding has implications both for the value of oceanographic temperature mapping and for pollution studies. One resulting activity taking place is called the Mid-Ocean Dynamics Experiment [55].

We have already discussed some of the nuclear power reactor activities. Here the need is for stable, accurate fuel centerline temperatures in a hot, intensely radioactive environment, and similar stability in hot liquid sodium (LMFBR) or hotter gaseous helium (HTGR) [56]. In the geothermal power search, the emphasis is on stability and accuracy of rock temperatures, both to identify potential sources of geothermal power and to monitor the depletion, with time, of a given source [57]. An accurate, quick method for determining the enthalpy of liquified natural gas is an essential feature of equitable custody transfer, and this is not available.

The ability of a competent instrumentation scientist to influence the growth of medical practice has been described in terms of "forcing a definition of the real requirements of a measurement need to avoid simply making gadgets for the M.D." [58]. Another opportunity is in the coming use of fluidic sensors to measure turbine inlet and outlet temperatures [59]; such a device is in increasing use in the aircraft industry, but, though it is both durable and stable, its temperature characteristics are relatively unknown [60].

Many applications of infrared sensing have been developed, and each of these contains the potential for temperature mapping on both a fine and a macro scale. Such activities as thermal pollution monitoring, plant and soil field studies, paper processing, rubber and textiles curing, printing and painting, food processing, and microcircuit analysis are all currently in operation. However, the temperature data which would allow correlation with other variables is very qualitative, because of uncertainties in calibration [61].

3. IMPACT, STATUS, AND TRENDS OF THE NATIONAL TEMPERATURE MEASUREMENT SYSTEM

3.1 Impact of Thermometry Measurements

3.1.1 Functional, Technological and Scientific Applications

We have already noted that thermometry touches virtually every person in the U.S. The quality of thermometry routinely available governs his health, his comfort, and often his manner of earning a living. The major manufacturing industries depend to a great extent on high-precision temperature measurement and control. Finally, scientific research in many areas produces useful data only to the extent that it employs sound, accurate thermometry. Some examples of these applications follow.

a) Thermometry in Medicine

Clinical laboratories are becoming highly automated in their testing and a large fraction of the results obtained are sufficiently sensitive to temperature to demand that small, stable, highly sensitive, accurate, and rapidly-responding temperature sensors be used. Those sensors should also be capable of producing electrical signals that can be digitized in order to be used with data recording and analysis systems.

In instruments for enzyme rate analysis in which samples of only a few microliters are used, the requirements for accuracy, response time and size of the temperature sensor are paramount, and in instruments for acidity and blood gas analysis, temperature measurements in the immediate vicinity of the measuring electrodes require small, accurate sensors. In routine clinical tests that are presently being performed, temperature errors produce such a variation in the results of enzyme tests that comparisons among laboratories, and even within a given laboratory, are useless. This is a sad state of affairs, especially when one realizes that inadequate thermometry in clinical laboratory tests may result in incorrect diagnosis and improper treatment of the patient.

At the present time, 20% of all temperature measurements of patients in hospitals and in physician's offices are taken using rapid, disposable and inexpensive temperature sensors which are rapidly displacing conventional mercury-in-glass thermometers and, yet, these sensors have not been adequately evaluated!

Just as in the case of the electronic fever thermometers, the temperature sensors in use today throughout the medical field appear to have many of the required qualities, but they have never been adequately characterized. In addition to having sensors with the desired properties, it is necessary to be able to check their calibrations periodically in the field or to enable new calibrations to be made accurately. The best way of doing this would be through the use of a set of standard temperature-reference-points in the range of biological interest and a practical simple mechanism to relate the patient temperature measuring instruments and the various devices utilized in the clinical laboratory to those reference points. None exists at the present time.

Miniature temperature sensors which are insensitive to electromagnetic fields are needed in order to be able to determine the temperature distributions produced in tissues being irradiated by the electromagnetic waves in diathermy (a medical treatment in which heat is produced in the tissues by a high frequency electric current). Temperature mapping the tissues is required in order to set standards of safe levels of electromagnetic radiation from the diathermy machines. This technique is required since direct measurements of electromagnetic field intensities in tissue are difficult to perform, and, in any case, temperature is the critical variable inside the tissue. Heretofore, such temperature measurements have not been performed in a satisfactory way.

b) Thermometry in Building Design and Comfort

Human thermal comfort has always been a consideration in the design of buildings, whether homes or businesses. In the "good old days" when energy was plentiful and inexpensive and buildings did not need to be so carefully designed, the thermostat in the room or building could be set such that one would be comfortable at any given location in the room. When his location was changed to a different part of the building or even a different part of the same room, however, it is very likely that a change in the thermostat setting would be necessary in order for the person to be made comfortable again. Since energy required to keep one comfortable is now very expensive and becoming more and more so with likelihood of an energy shortage, well insulated buildings designed with human thermal comfort maintained by a minimum use of energy are a prime consideration.

A number of different types of thermometers have been used by design engineers and probably the one most widely used at the present time is the globe thermometer. This is a very crude thermometer system which attempts to measure the mean radiant energy over a solid angle of 4π steradians. Such a thermometer is not a good indicator of human thermal comfort. This can easily be seen by a simple example. The human body is, to a first approximation, a 2-dimensional system and if a person is near a fire, then one side (say his front) is exceedingly hot whereas the other side (his back) may be excessively cold. As a result of this exchange of radiant energy, the person is most uncomfortable but since the globe thermometer measures the mean radiant energy over 4π steradians, it would indicate a temperature which would be pleasingly comfortable to the person. This, then, points up the problem with such a thermometer.

We have noted earlier, of course, that the home, office, and factory are heated and cooled according to temperature-sensitive controls which operate furnaces, fans, refrigeration units, and sometimes ventilating windows or doors.

c) Thermometry in Manufacturing

One may consult the Standard Industrial Classification Codes noted in Table 2.5A for an indication of the groups of manufacturers which employ thermometry.

The uses to which temperature measurement amd control are put include steel making (not only to adjust the furnace temperature itself, but also to monitor and control the temperature of gas streams, cooling ingots and coke ovens as well), manufacturer of both ferrous and non ferrous metal products (chiefly in heat-treating furnaces), and food preparation (much of the U.S. food preparation industry utilizes assembly-line manufacturing principles. techniques, and instrumentation) which involves storage temperature measurement and control as well as process control.

A great variety exists not only in the wide-ranging products of U.S. manufacturing, but also in the thermometry techniques which it employs. Liquid in glass or metal thermometer systems, bimetallic, resistance, and thermoelectric thermometers, and radiation pyrometers are used individually or in concert to measure, record, and control temperature in manufacturing.

d) Thermometry in Science

The variety of thermometers employed in scientific research and development is nearly as great as that used in manufacturing. High-precision resistance or quartz oscillator thermometers are used in calorimetric studies and in other physical and chemical thermal data acquisition. Less precise but more versatile or smaller thermometers are employed in basic studies where temperature is not of primary importance. The range of temperature which is measured and controlled in scientific experimentation ranges from above the melting point of the most refractory material (as, for example, in research on thermonuclear fusion) to within one degree of absolute zero. Innovation is the order of the day in much of this work, and most advances in thermometry arise from the efforts of scientists to measure and control temperature.

3.1.2 Economic Impacts - Costs and Benefits

Some idea of the costs involved in the use of thermometry equipment by the National Temperature Measurement System has been given by figures quoted earlier in this Study. For example the annual sales of thermometers exceed $5 million just in ASTM-specified liquid-in-glass; electrical and electronic thermometer sales in 1972 exceeded $40 million; over $10 million worth of thermistors are sold annually; annual sales of thermostats for heating and cooling exceed $280 million.

Such figures indicate the economic magnitude of thermometry (which is clearly enormous in itself and possesses a great deal of leverage to boot, since thermometry comprises only a small portion of the value of manufactured goods), but they do not address the individual questions of the benefit which may be derived by a given company or industry upon introducing more effective thermometry. This latter type of information is difficult even for an individual company to obtain in a reliable way. Still less visible is the cost of not introducing improvements in technology such as thermometry.

This study has benefited from the advice of trained economists in numerous ways, from simple familiarization with economic statistics to the principles of technical-economic forecasting. A detailed discussion of the cost-benefit relationship in the National Temperature Measurement System is out of the question as a practical matter and, we think, beyond the proper scope of this study. Even this brief overview of the System, however, makes abundantly clear the general situation that thermometry investments in the National Temperature Measurement System are large and growing and that the use of automatic thermometry equipment is increasing steadily.

3.1.3 Social, Human, Person-on-the-Street Impacts

The major benefits of thermometry in many social terms relate, for example, to the precision and efficacy of medical treatment; people are alive today because U.S. Industry has provided U.S. medicine with a certain level of quality of thermometry. (We have *not* reached the millenium in this particular area, however, as we have seen!) They relate also to his safety, as temperature control of dangerous systems such as chemical processors and boiler plants has improved to the point that serious plant accidents are rare. They relate as well to his comfort and standard of living, insofar as he owns a thermostated oven, toaster, automobile, home, air conditioner, laboratory, hot water heater, office, greenhouse, or any manufactured item for which the materials of construction owe their properties to the careful temperature control which is now so widely available.

3.2 Status and Trends of the Temperature Measurement System

In coming to grips with the National Temperature Measurement System, its current status and trends, we called upon the personal knowledge accumulated by our staff over the years. We found that we had great stores of data on sensors, their stability and calibration properties, and that we had a limited knowledge of the needs of various people.

The real core of the National Measurement System is, of course, people. Only people and the purposes of people given meaning to thermometric devices and the numbers which come from them.

In attempting to analyze the "National Measurement System" for temperature, we realized that only by becoming conversant with the activities of people in many different occupations could we begin to understand their interrelationships and to identify their capabilities and needs.

The best way to familiarize ourselves with the activities of the National Temperature Measurement System is by face-to-face discussion and laboratory or plant visits. In such extended contact we obtained some or all of the following types of information:

1) The nature of the group's thermometry interest;
2) the relevance of this interest to other group's activities and to national problems;
3) the practical precision and accuracy desired, and that realized;
4) relevant economic data--costs or sales of calibrations, sensors, thermometry or associated equipment;
5) impact of their work upon national, industrial, or social problems;
6) value of NBS thermometric services to their own activities, and particular needs which NBS might be

able to supply.

Travel restrictions, coupled with the large expenditure which travel involves, have the effect of limiting the amount of such face-to-face discussion. The effectiveness of telephone or mail contact in eliciting the type of information we seek is not nearly so great, unless a previous contact with the individual has created an easy relationship.

As a consequence of several such familiarization visits, we were able to discern patterns which allow us to separate groups of people according to the manner in which their activities impinge on thermometry.

Underlying the whole structure of the National Temperature Measurement System is the International Practical Temperature Scale. NBS thermometricians improve the scale with the help of academic researchers who, though an independent lot, bring solid accomplishments to strengthen the scale.

It is only a little oversimplification to describe the three NBS calibration services as the main pillars of support for the rest of the structure: in fact we have found a universally high regard for these services and a desire to see them more widely available.

The NBS provides calibration services to the various sensor manufacturers, although, as we have indicated, the thermistor industry needs special help. In turn, the sensor manufacturers support the temperature control equipment manufacturers and the large government and commercial temperature-calibration facilities.

Finally, the commodity industries, both large and small, rest strongly upon the combined bases of temperature control devices and sensors.

Another aspect of the National Temperature Measurement System concerns health and safety in thermometry. We found, in this area, that the problem of medical temperature standards is severe. Doctors J. H. V. Brown and D. J. Lowell of Health, Education and Welfare discussed the question of standardization and health care in a cogent article which points out that, with acequate standardization, the medical profession could well concentrate on maintaining the health of the 220 million citizens rather than simply curing the 1.3 million sick. There are no widespread criteria for manufacture of hospital equipment to prevent electrical shock, they say; inadequate control of pacemaking equipment is rampant; the safety of ultrasound and microwave equipment is completely unevaluated; clinical tests are widely variant from hospital to hospital and even within a single lab; and the medical community really doesn't know how to set up standards. They suggest that the Federal government guide the medical profession and the instrument manufacturers in this task [1]. A similar theme is sounded by R. S. Melville of the National Institute of General Medical Sciences, who notes the lack of adequate clinical laboratory standards and the formation of a Committee for the study of automation in medical laboratories; he stresses the utility of microcalorimetry work at NBS (in the Thermochemistry Section) and of the Standard Reference Materials program [2]. Mal Schechter, writing in Lab World, urges Health, Education and Welfare and National Institute for Occupational Health and Safety to work with American National Standards Institute, the National Committee for Clinical Laboratory Standards, and NBS on comprehensive medical standards [3]. Dr. Nathan Gochman, Chief of Clinical Chemistry for the Veterans Administration Hospital in San Diego, focused on temperature as a vital parameter in a talk on automated clinical testing, in which he pointed out that the use of enzyme analyses and other temperature-dependent tests enhance noticeably the requirement for temperature standardization and control [4]. As will be noted in Section 4, NBS is beginning a comprehensive program of measuring the relatively unknown characteristics of the ubiquitous thermistor, and of providing the technical leadership for medical standardization.

The regulatory agencies, too, have difficulties. One example of this problem is a recent case before the New York Public Utilities Commission involving the relocation of the official thermometer by the Orange and Rockland Utilities, Inc.; the utility had moved the thermometer from a relatively protected position to an unsheltered one, and sought rate relief of $1 million based on the colder readings [5].

An enormous current and developing problem centers around automotive pollution and mileage; we noted earlier that automotive design is often unscientific, in part owing to poor thermometry in design. This leads to mediocre mileage-to-weight ratios. Emission control also suffers from poor thermometry. Privately, the industry admits that health and safety considerations rank low in its priority listing [6]. The regulatory agencies, however, must decide on workable goals in the face of conflicting arguments; the auto industry has been described by the Secretary of Commerce as "spending nearly $2 billion in 1973 on safety and emission standards" [7], and the Coordinating

Research Council-Air Pollution Research Advisory Committee has been both criticized as an industry slave [8] and praised as an independent force [9]. P. G. Hansel, Vice-President of Research for an NCR subsidiary, recently called for major programs to enhance engine efficiency [10]. Accurate measurement of temperature and pressure in each cylinder and an electronic gasoline control system are being considered as a mechanism for reducing emissions and improving mileage of automobiles.

The problems of the medical community also occur, of course, with respect to regulatory agencies. We have already alluded to the uncertainty of ultrasonic and microwave diathermy safety. The reliability of electronic thermometers [12] is also regulatory concern of FDA, as well as of several states. The principal challenge to NBS is to provide useful guidance to these agencies within their relatively short time requirements.

In the various power and energy areas, we find the active people uncertain as to how to proceed with measurement and control problems. In the very active area of nuclear power reactors, the question of public safety is the subject of continuing controversy. Fortunately (for the NBS thermometry program, that is) the primary controversy centers around *radiation* safety [13]. However, the lack of really adequate temperature measurement capability has contributed to the difficulty of introducing substantial quantities of nuclear power into the U.S. energy network [14]. The U.S. currently has about 17,500 megawatts of nuclear power--about 10% of that currently projected to 1980. This is about the same amount of power as is produced by TVA from non-nuclear sources [15,16].

Finally, in the area of commodity manufacturing, the problems of health and safety often are not readily visible, and they often are not willingly exposed to view.

Another area of immediate concern is that of industrial standards. We believe the keys to this situation are information and cooperation, with NBS data and technical advice connecting the individual manufacturer and standards groups and among the various standards groups themselves.

In forming these ideas, we drew upon many years of combined experience of service to the National Temperature Measurement System (although we have not always thought of it in those terms) and upon familiarization visits to particular facilities.

During the past year or so, we have visited well over fifty facilities of various types. We attempted to visit power manufacturers, aerospace manufacturers, regulatory agencies, medical research and health care facilities, government calibration laboratories, oceanographic facilities, temperature control and temperature sensor manufacturers. In addition, we have attended numerous scientific, technical, and commercial standards meetings.

As a consequence of these visits, it became obvious to us that we could significantly affect the quality of medical patient care in the U.S. by undertaking a combined technical and liaison program in medical thermometry. Reprogramming of personnel to this end has enabled us to begin already a 3-4 person effort which is more fully described in Section 4.

We have found, as might be expected, that many parts of the National Temperature Measurement System have generated ways of solving their own problems in temperature. One case which is worth citing is that of critically evaluated data, in which an attempt is made to analyze existing data to arrive at "best values" for a given quantity [17,18]. The NAS/NRC has sponsored a Report on Physics in Instrumentation, in which the integrity and needs for thermometry instrumentation are evaluated. Many professional associates have sponsored research groups, such as the American Gas Association and the Electric Power Research Institute, and many non-NBS groups sponsor meetings and research projects on thermometry and control. A few examples of these are the ORNL Instrumentation and Controls Division Annual Information meeting; a course on Measurement Systems Engineering given annually by Arizona State University; and "Physics Opportunities in Energy Problems", offered by the American Physical Society in February 1974.

Although sufficient to give us a picture of the basic status and trends of the National Temperature Measurement System, the field investigations conducted to date are by no means sufficient either to delineate completely the natures of the various groups or to point the way unequivocally to correct courses of future action. To these ends. we have outlined further specific inquiries which we shall note later.

4. SURVEY OF NBS SERVICES TO THERMOMETRY

NBS has contributed to the National Temperature Measurement System since the Bureau was established in 1901. In this section, we will present some discussion of early contributions and we will detail the nature of present activities. It should be noted at the outset that the present thermometry activities cross Institute as well as Division lines, and we made a definite attempt to present a balanced view of NBS thermometry without chauvinism. The reader can easily determine how well we succeeded by soliciting comments from outside the NBS Heat Division.

4.1 The Past

From the first International Temperature Scale of 1927 (submitted by NBS, NPL, and PTR, and described for the U.S. public by G. K. Burgess, at that time director of NBS) [1], the National Bureau of Standards has maintained a leading role in U.S. thermometry: With the National Research Council, NBS cooperated in preparing the 1939 Temperature Symposium and provided half of the papers on temperature scales and on precision thermometry [2]; NBS established temperature calibration facilities for the various standard instruments (Over 500 firms were listed among recent calibration services customers). With the AIP and the U.S. Army, NBS sponsored the 1954 Temperature Symposium and again contributed key papers on fixed point apparatus and temperature scales [3]; similar comments apply to the 1961 and the 1971 Symposia; in addition, NBS has disseminated tables, monographs on measurement techniques, and original research in thermometry through journal articles, colloquia, seminars, and other scientific meetings.

Two very useful compilations of NBS thermometry contributions are Vol. 2 of NBS Special Publication 300, "Precision Measurement and Calibration-Temperature" [4] and its companion volume on Heat [5]. The former contains an assortment of papers on temperature scales including IPTS-48; the 1939 Hoge-Brickwedde gas-thermometer scale recorded on platinum resistance thermometers between 14 °K and 83 °K; its correction in 1955; the 1965 NBS 2-20 K velocity of sound scale of Plumb and Cataland; and the 0.002-2 K scale based on the paramagnetism of cerous magnesium nitrate by Hudson and Kaeser. In addition, there are resistance, thermoelectric, liquid-in-glass, and spectroscopic thermometry and optical pyrometry; in all, some twenty-five papers.

The latter volume likewise is a mine of NBS expertise, this time in the general field of calorimetry, with many of the thirty-odd papers being of fundamental importance to thermometry.

It is worthwhile to review the NBS contributions to the Fifth Temperature Symposium, [6] since a good idea of the level of NBS thermometry can thus be gained. R. P. Hudson, Chief of the Heat Division; H. J. Kostkowski, Chief of the Optical Radiation Section; H. H. Plumb, Chief of the Temperature SEction; and W. R. Tilley, Chief of the Office of Technical Publications served on the General Committee. H. H. Plumb was Chairman of the Program Committee, assisted by H. J. Kostkowski, R. D. Cutkosky (Electricity Division), and R. L. Powell (Cryogenics Division) in addition to the twenty or so members from outside NBS.

In the technical program, NBS contributed some 27 papers ranging in nature from very fundamental thermodynamic thermometry to temperatures in building environments.

All of the foregoing Section represents only a portion of the thermometry activities of NBS in the recent past. Consultations, reports to sponsors, other publications and contributions to other scientific meetings must be added to complete the picture.

4.2 The Present--Scope of NBS Thermometry Activities

4.2.1 Description of NBS Thermometry Services

In order to give the reader a flavor of the range of thermometry activities at NBS we shall note recent accomplishments of the appropriate programs. In the next subsection we shall review the thermometry programs within the Heat Division [7], and subsequently other thermometry highlights within NBS.

4.2.1.1 Heat Division Thermometry Activities, 1974

The new year brought a change in leadership to the Temperature Section. R. P. Hudson, Chief of the Heat Division, acceded to H. H. Plumb's long-standing desire to return to a more active scientific role in the Section's activities, thus bringing to an end an era that began in October, 1966.

Under Dr. Plumb's leadership, the Temperature Section gained both stature and versatility. In 1966, over 50% of the Section's effort was devoted to calibration activities; this figure is now below 20%. Projects have been initiated in calorimetric measurement of thermodynamic temperatures, in medical thermometry, and in a continuing study of the national temperature measurement system. The Section participated closely in the formulation of the new Temperature Scale [8], and it is presently represented on two of the four working groups of the CCT which were in existence in January, 1974, as well as on the temperature committees and subcommittees of both the American Society for Testing and Materials and the American National Standards Institute.

Several of the highlights of the year's activity in the Temperature Section appear in the Minutes of the May, 1974 meeting of the CCT at the International Bureau of Weights and Measures (BIPM) in Sévres, France [9]. The National Bureau of Standards was represented at that meeting by R. P. Hudson, Chief of the Heat Division, and by H. H. Plumb. Technical contributions were submitted by staff members of the Cryogenic Physics Section, of the Equation of State Section, and of the Temperature Section. A summary of the Temperature Section contributions follows:

1) A brief discussion of the cryostat and methods used in the calibration of capsule platinum resistance thermometers from 13.81 K to 90.188 K;

2) recent gas thermometry results which provide information on the differences between the IPTS-68 and thermodynamic temperatures from the triple point of water to 415 K (142 °C). Working group 3, of which L. A. Guildner is a member, reported it;

3) a brief description of apparatus, currently under construction, for the comparison of standard platinum resistance thermometers (SPRT's) from 90 K to 900 K;

4) the results of a study of the freezing temperatures of six experimental aluminum freezing-point cells; and

5) editorial suggestions regarding changes in the text of the IPTS-68. Consideration of possible revisions of the text was a particular duty of Working Group 1 of the CCT, of which H. H. Plumb is a member.

As usual, the Section offered a week-long seminar on precision thermometry. The attendance, however, was more than double the usual number. Some twenty-seven participants crowded the calibration laboratories during the week of 10-14 March. In addition to providing both that seminar and a three-hour thermometry session which formed a part of a local university's short course in standards laboratory operation, the calibration staff tested over one thousand precision thermometers and answered a like number of written and verbal inquiries on thermometry to round out a very satisfactory year.

The Section's work in thermocouple thermometry included the publication of the long-awaited Thermocouple Reference Tables, Monograph 125, and highly successful study of a new high-temperature nickel-silicon-chromium thermocouple system developed in Australia.

The low-temperature acoustic thermometer program yielded results of thermodynamic measurements of the transition temperatures of two elements of the NBS superconductive fixed-point device.

The medical thermometry program, begun only a year ago but now the largest in the Section, has made rapid progress toward its goal of improving the nation's medical care by improving the quality of thermometry in medicine. New precision clinical laboratory thermometers were developed, equipment and procedures for characterization of thermistors and small platinum resistance thermometers were completed, collaborative work on an environmental scanning radiometer and on thermometry in medical diathermy was accomplished, and exchange of equipment and ideas took place between the medical thermometry group and staff members of hospitals, clinics, and medical instrument manufacturers.

Closely allied to the field of medical thermometry, as well, is a new project begun in the past year by W. S. Hurst. Partially funded by the National Institutes of Health, this project will be an experimental study of thin-film capacitance thermometry.

R. J. Soulen is utilizing a sensitive superconductive tunnel junction to determine noise temperatures according to the Nyquist theorem. This technique was suggested by R. A. Kamper of the Cryogenics Division. At present Soulen's results agree within ±2 mK from .02 - .04 K with results of yet another thermodynamic temperature determination undertaken by H. Marshak. These latter measurements involve the measurement of the anisotropy of γ-radiation emitted by 60-Co nuclei in a single crystal of cobalt; the various nuclear data determine the anisotropy due to decay of nuclei in the magnetic energy levels, and the Boltzmann distribution function governs the level populations.

In addition to the cryogenic physics discussed above, Heat Division programs include the generation of Superconductive Thermometric Fixed Points from 0.5 K to 7 K, developed as NBS Standard Reference Material 767 by J. F. Schooley and R. J. Soulen, Jr. [10], and study of paramagnetic sensors below 20 K by B. W. Mangum and D. B. Utton. The overall Cryogenic Physics Thermometry Program is discussed in some detail in NBS Technical Note 830 "NBS Cryogenic Thermometry and the Proposed Cryogenic Extension of the IPTS".

In this section, an indication has been given of the range of NBS activities in temperature standards. Appendix D lists most (dare one say *all*?) of the NBS staff members who officially participated in these activities.

To this catalog we add a recent anecdote which may be illustrative of NBS' role in industrial standards. Having joined the International Organization for Legal Metrology (OIML) in August, 1972 [11], the U.S. was given the opportunity to vote on a current draft recommendation on electrical resistance thermometers composed of Pt, Cu, and Ni (PR 41). In order to develop a position on the recommendation, J. Schooley distributed copies of it during the ASTM Resistance Thermometry (E-20) Committee meeting in June, 1973. Other copies were distributed to interested companies who were alerted by ASTM. In all, correspondence took place with some two dozen firms. Their comments on the draft were consolidated into a U.S. response with the help of Mr. E. D. Zysk, of Engelhard Industries, a representative to IEC, and Mr. J. E. French of the Scientific Apparatus Manufacturers Association. Mr. W. E. Andrus, U.S. representative to OIML, communicated this (negative) response officially [12].

4.2.1.2 NBS Thermometry Activities Outside Heat Division

a) Thermal Efficiency of Buildings

Temperature measurements play a large role in several parts of the Center for Building Technology programs. One of these, Project Breakthrough [13], was commissioned by HUD to examine the feasibility of applying the principle of overall energy consumption to a building complex; all the "waste heat" from the power generators is to be used for building air and water heating. P. R. Achenbach and J. B. Coble are attempting to assess the economic features, including the heat balance, of the complex. A similar program is underway with HUD, AEC, NASA, and EPA cooperation [14]. Since 20-25 percent of the nation's energy use goes for space and water heating or for lighting, significant power savings can result from these programs.

The Center also has an experimental townhouse in which the thermal balance is measured. B. A. Peavy, D. M. Burch, J. D. Allen, and D. R. Showalter have instrumented the house heavily, including some 140 air-temperature sensors and 58 wall and window surface temperature probes [15]. The CBT environmental test chamber provides a temperature environment ranging from -50 °F to +150 °F. In one recent study, the fuel economy of nighttime reduction of the thermostat set point was evaluated and shown to be quite substantial.

In other, related CBT programs, T. Kusuda and F. J. Powell are studying thermal storage and heating cycles in buildings [16]; and J. Stern and S. Edelman are studying plastic infrared detectors [17] and their use in scanning thermal detectors [18].

b) High-Speed Thermophysics

A. Cezairliyan, of IMR, has been studying for some time the simultaneous measurement of a variety of thermophysical properties of refractory metals. In addition to such information as electrical resistivity and heat capacity, he obtains temperature values for the sample data by optical pyrometry. Recently, this technique provided information on the thermal properties of niobium alloys in the range 1500-2700 K [19]. In addition, Dr. Cezairliyan has studied the relation between radiance temperature and actual temperature at the melting point [20].

c) Microcalorimetry

Microcalorimetry is a science which is of particular value to research biochemists and to clinical laboratories because of its ability to analyze extremely small samples. This very requirement, of course, brings its own emphasis on the use of small, sensitive thermometer probes. NBS, in its Thermochemistry Section of IMR, has a very active group including G. T. Armstrong, E. J. Prosen, R. N. Goldberg, R. N. Boyd, B. R. Staples, and M. V. Kilday. An NBS clinical microcalorimeter which was described in a recent report [21] uses a quartz thermometer (sensitive to $\pm 10\ \mu K$) for overall temperature stability evaluation, and a thermopile is used in the primary energy detection.

4.2.1.3 The NBS Thermometry Input-Output Table

The present activities of NBS in thermometry can be summarized in a variety of ways. Perhaps the most useful technique would show a dollar value which each portion of the program provides to the various components of the national measurement system, but this technique is absolutely beyond the competence of mere scientists, involving as it does an economic evaluation of basic temperature scale studies which predate their useful consequences by many years. Two methods, however, are at once feasible and useful. One of these is the source-output diagram, and the other is a national needs-thermometry activities matrix.

In the source-output table 4.2A, we attempt to show the origin of the current thermometry activities (which we have discussed briefly in this section) and the major outputs which result from these activities. The distribution of calibrations, research efforts, and consultations over the various user areas conspire to make the estimates of the percentage outputs very uncertain; however, these numbers may be useful even in a qualitative way.

Table 4.2A

NBS Thermometry Request Sources

NBS - Provide direct requests for calibrations and consultations. Electricity Division, Physical Chemistry Division, Mechanics Division, Optical Physics Division, Cryogenics Division, Analytical Chemistry Division, Polymers Division, Electromagnetics Division, Metallurgy Division, Inorganic Materials Division, Electronic Technology Division, Structures, Materials, and Life Safety Division

Industrial Requests - For sensor development and characterization, calibration, thermometry consultation. ~500 individual firms, 10-12 trade associations

Voluntary Standards Groups - Provide direct requests for technical guidance in writing standards. Provides information on current and planned development in scale work. CCT, ASTM, ANSI, IEC, ISO, OIML

Regulatory Agencies - Provide direct requests for consultation and measurement services. Provide information on future needs. FDA, HUD, EPA, OSHA

Other Government Agencies - Provide direct requests for calibrations, consultations on thermometry problems. Provide information on future needs. USN, USA, USAF, NOAA, AEC, NASA, HUD, DOT, NIH

Medical Groups - Provide direct requests for calibrations, and consultation. Provide information on future needs. NCCSL, CAP, Medical Instrument Manufacturers, Individual hospitals, physicians, and medical researchers

Thermometry Equipment Manufacturers - Provide direct requests for calibration and consultation services. Provide information on state-of-the-art design. ~100 firms, ISA, SAMA

University Researchers and Professional Journals - Provide information on advanced thermometry principles and techniques. Provide collaboration on research and development problems. ~1000 universities, ~50 journals

NBS Outputs, with Percentages

10%
NBS - Calibrations. Consultation. Colloquia. Reports.

10%
Industrial Firms - Calibrations (~$75,000 in FY-73). Consultations. Reports.

10%
Voluntary Standards Groups - Meetings attendance (~100 estimated in FY-74). Technical evaluation of standards proposals (~10 estimated in FY-74).

5%
Regulatory Agencies - Consultations - OSHA, FDA, HUD, DOT, EPA. Reports.

25%
Other Government Agencies - Calibrations (~$40,000 in FY-74). Reports on sponsored research (estimate $500,000).

15%
Medical Groups - Calibrations (~$15,000 in FY-74). Reports on sponsored research. Consultations.

10%
Thermometry Equipment Manufacturers - Consultations. Calibrations (~$20,000 in FY-74).

15%
Scientific Research Journals - Scientific papers (~50 in FY-74). Colloquia.

4.2.2 Users of NBS Services

The major users of National Bureau of Standards thermometry services have been identified in Section 2.5. They comprise the "Knowledge Community" (Scientific and Educational groups), Metrological and Standards bodies, the Thermometry Instrumentation industry, NBS itself, government and commercial calibration laboratories, various government agencies, manufacturing groups, and health services. Typical examples of their uses of NBS services are the employment by a thermometry manufacturer of a calibrated Standard Platinum Resistance Thermometer to determine the accuracy of a production temperature sensor-readout system; and the conversion by a new company of NBS instruction on the manner of establishing a calibration laboratory, into a set of orders for space, environmental control, and precision thermometry equipment.

4.2.3 Alternative Sources

It is difficult to say how the various thermometry responsibilities of the NBS would be met by the National Temperature Measurement System in the unlikely circumstance that NBS were to cease to exist.

The fundamental difficulty with such a step would lie in the responsibility of NBS to participate with other industrialized nations of the world in maintaining a uniform International Temperature Scale which is based on thermodynamic measurements. This is a very expensive undertaking, since it demands the long-term involvement of highly-qualified scientists. We know of no organization--governmental, university, or industrial--which could commit sufficient resources to meet this responsibility. Thus any such attempt would necessarily involve a consortium of organizations with the attendant management problems.

A similar difficulty appears in meeting the responsibility of Scale dissemination. A likely solution would entail the verification of Scale integrity by each of the major industrial and governmental calibration laboratories. This solution carries with it the inherent problem that a given laboratory would have a financial stake in minimizing the expense involved in certifying the accuracy of its thermometric measurements. The lack of objectivity in such a system would almost certainly lead eventually to the generation of a "National Bureau of Regulatory Standards" somewhere within the federal government.

The easiest of NBS' current responsibilities to meet is that of contributing to broad, general problems in thermometry measurement science. In thermometry these problems are met by very small NBS efforts —two-to four-person programs undertaken in collaboration with university, governmental, or industrial groups. The efforts are commonly mounted in response to needs perceived as affecting an entire industry or measurement area. The fact that the NBS efforts in these general areas are miniscule in comparison with those of other government or industrial laboratories, coupled with the fact that workers in the particular areas involved are generally motivated to solve their own problems, indicate that the NBS efforts here are the least essential of its services. A modicum of foresight and modest resources would permit the NBS effort in applied thermometry to be duplicated elsewhere. The missing elements in this solution are those which NBS can contribute in special circumstances: organizational resources to bring particular problems to light as is done in periodic workshops and conferences generated by NBS; objective expertise to apply to important national questions such as the quality of particular energy-conserving measures or effective means of improving U.S. medical care by application of more relevant standards of thermometry; and the combination of state-of-the-art facilities, expert staff, and flexibility in programming to "bear down" on a particular problem before it becomes a bottleneck to progress by a whole industry.

4.2.4 Funding Sources for NBS Thermometry Services

Overall, NBS thermometry is funded about 50% from external sources and 50% by direct congressional appropriation. The outside funding support comes chiefly from calibration income and the Executive Departments of Health, Education, and Welfare, of Housing and Urban Development, and of Defense.

The distribution of this funding is not uniform throughout the NBS programs, however. Most of the outside funding accrues to applied thermometry programs outside the Heat Division (excepting calibration income), while the major direct appropriation support goes to Heat Division scale research and dissemination activities.

The following summary of Fiscal Year 1974 funding of the Cryogenic Physics and Temperature Sections (the two principal thermometry activities of the Heat Division) helps to illustrate this situation.

Table 4.2B

Cryogenic Physics and Temperature Sections,
Funding by Source, Fiscal Year 1974

Source		Percent
NBS		
Direct Appropriation		80
Standard Reference Materials		1
Other NBS Divisions		1
	Total NBS	82
Other Government Agencies		
National Oceanographic Administration		1
Food and Drug Administration		3
Department of Justice		4
	Total OGA	8
Calibrations		10
	Grand Total	100%

4.2.5 Mechanisms for Supplying Services

The dissemination mechanisms by which NBS supplies its thermometry services take many forms, reflecting the diversity of NBS activities. Most of these have been discussed elsewhere in this study and will be mentioned here only briefly.

Scale Research results are communicated to the general scientific community through articles published in the open literature. In addition, direct communication is made to the International Thermometry Committee (the "CCT") of the General Conference on Weights and Measures both in written reports and by verbal presentation at periodic meetings.

Calibrations are rendered upon thermometry equipment owned by governmental and industrial laboratories. Test results are given in written form and occasionally analyzed as a class to yield information on the overall precision and accuracy of NBS temperature calibrations. These summaries are made available to the public in general through the NBS Technical Note series.

Measurement Assurance Programs, Consultation and Instruction involve the NBS staff directly with individual governmental, industrial, and medical thermometrists. Test summaries, recommendations, handbooks and instructional materials are written and distributed during discussions with the users of these services.

Basic and Applied Thermometry results and services are communicated through the writing of reports-to-sponsor, NBS technical publications, or research papers. In addition, of course, lectures, seminars, and technical meetings serve as outlets for this type of information. In many cases, particular devices make up a portion of these services.

Standard Reference Materials and Data results appear as items for sale through the Office of Standard Reference Materials (listed in the NBS Special Publication 260), or as reference tables or other data published in the NBS Monograph series.

Voluntary Standards services generally appear indirectly. New or revised industrial standards often are based in part or wholly upon data or measurement techniques originating at the NBS. Examples of this activity arise primarily because the NBS thermometry staff actively participate in the work of the American Society for Testing and Materials, the American National Standards Institute, and their international counterparts. Writing and editing of publications issued by or at the request of such groups often falls to NBS thermometrists because of their great familiarity with the topic.

4.3 Impact of NBS Thermometry Services

4.3.1 Economic Impact of Major User Classes

The major thermometry users have been identified in Section 2. In terms of immediate economic importance, certainly the largest contribution comes from the manufacturers of durable goods. These people build and sell refrigerators, air conditioners, automobiles, aircraft, stoves, furnaces, furniture, and many other products which may include thermometers or thermometric controls or may simply require thermometric monitoring or control in their manufacture. These people are NBS thermometry calibration customers. It is difficult to assign a value added by NBS services to this group.

Mining, agriculature, chemicals manufacturing, and metals and plastics producers regularly send their highest quality thermometers to NBS for thermometry calibrations. Again the economic impact may be stated simply as "large".

The automatic temperature controls industry is separately classified by the Census Bureau. The various components of this industry annually ship goods worth several hundreds of millions of dollars annually. By this time, our listing is reaching groups whose representatives not only buy calibrations from NBS, but also consult frequently on measurement problems.

As the user-group output becomes more specialized, its direct and immediate economic impact is smaller, but its long-range importance appears to be larger. The manufacturers of thermocouple thermometers, resistance thermometers, liquid-in-glass thermometers, bimetallic and thermistor thermometers ship annually goods valued at $10-50 million in each subgroup. However, these products govern the quality and performance of those enormous user classes listed earlier.

Still longer range in economic impact is the government-funded research and technology activity, containing the U.S. executive Departments, the national laboratories, and federally funded laboratories in the industrial sector. NBS helps the people who staff these organizations in ways we shall note in the next section; and although their immediate economic impact is small (or negative!) their importance for the future of the U.S. is large.

4.3.2 Technological Impact of NBS Services

In addition to the obvious influence which basic research on the international temperature scale at all temperatures carries to the areas of competence in international trade and of the general improvement of the quality of U.S. goods and services, very specific technological improvements result from NBS activities in thermometry.

Among these improvements are techniques of calibration and measurement, which enable higher quality to be delivered for less expense; new knowledge of the characteristics of medical sensors, which permits their use at new levels of accuracy; new types of high-temperature thermocouples, leading to advances in the instrumentation and design of nuclear reactors, high-temperature turbines and engines, and high-temperature industrial processes; new accuracy in cryogenic instrumentation; new techniques for differential thermal analysis and other basically microcalorimetric applications; new knowledge of fast temperature measurement techniques; and more accurate and reliable thermal analysis of walls, buildings, and dwelling complexes.

A National Needs-Thermometry Activities Chart was devised in a series of meetings of the Temperature Section staff as a convenient means of monitoring particular areas where NBS thermometry efforts have an impact upon various national needs.

Table 4.3A contains a listing of various areas of importance to the nation in the first column. The second column contains a listing of many projects and services of the thermometrists at the NBS. Following each entry in column two is a list of numbers which denote the national needs which are, in part, met by the particular NBS service or project.

This method of presentation has provided us with the ability to see how our own programs impinge on national problems and indicate that we are more readily able to plan our programs with a perspective arising from consideration of those needs.

4.3.3 Pay-Off from Changes in NBS Services

Over the years, NBS has begun new services and dropped others, with consequent adjustments by the U.S. Temperature Measurement System. One such change was the cessation of calibrating fever thermometers. This change helped bring down the price of such thermometers, and it simultaneously forced the manufacturers to establish and regulate for themselves their calibration.

A second example of such a change is the institution of medical thermometry as a program in the Temperature Section two years ago. This change has already begun to show benefits in improved thermometry as well

Table 4.3A

NBS-National Needs Chart

National Needs

1. Energy
2. Measurement Assurance
3. Meteorology
4. Oceanography
5. Health
6. Safety
7. Environment
8. Consumer Protection (i.e., product integrity)
9. Industrial Standards
10. An Accurate Temperature Scale
11. Temperature Control
12. Temperature Measurement Systems
13. Thermal Pollution

Thermometry Activities	
1. Thermocouple Development	1, 5, 9, 11
2. Miniature Resistance Thermometer	1, 5, 9, 10, 11
3. Noise Thermometry	1, 9, 10
4. Radiation Thermometry	1, 5, 9, 10, 11
5. Fixed points	1, 5, 9, 10
6. Thermistor Characterization	5, 9, 10, 11
7. Transistor Thermometry	5
8. Calibrations	2, 5, 8, 9, 10, 11
9. Tiny Sensors	5
10. Microcalorimetry	5, 9, 12
11. Electronic Thermometers	5, 8
12. Liquid Crystals	5, 9, 10
13. Quartz Thermometers	3, 4, 5
14. Safety in Thermometry	6
15. Theory of Thermometry	10, 11, 12
16. Regulatory Agencies	5, 6, 7, 8
17. Practical Thermometry Tips	2, 8, 9
18. Intercomparison of Standard Platinum Resistance Thermometers	2, 10
19. Gas Thermometry	9, 10
20. Transient and Dynamic Thermometry	1, 2, 3, 4, 9, 11, 12
21. New Equipment Development	2, 9, 11, 12
22. Cryogenic Sensors	1, 2, 10, 11, 12
23. Nuclear Resonance Thermometry	10, 12

as an increased awareness of the importance of accurate thermometry to effective medical practice.

As thermometry projects at the NBS are completed, or reach a point where further work would bring diminished returns, the institution of new projects becomes possible (in the present climate which prevails throughout the U.S. economy, NBS is making every effort to maintain a lively effective standards program without overall growth in its staff).

A large part of the advance planning prior to such opportunities concerns explicit questions of scientific and technical payoffs accompanying various options. These are necessarily balanced against questions of available facilities and major strengths in the thermometry staff.

4.4 Evaluation of NBS Thermometry Program

The NBS thermometry program is continually evaluated by its own staff and by NBS management in periodical reviews. In addition to these self-appraisals, an explicit evaluation of the program is supplied by a panel of experts on an annual basis. The Evaluation Panels have been established through the National Academy of Sciences in conjunction with the National Academy of Engineering and the National Research Council.

The Heat Division Evaluation Panel is made up of some ten members, which in recent years have represented the following organizations:

- Argonne National Laboratory
- University of Illinois Center for

Advanced Study
- Pennsylvania State University, physics department
- Eastman Kodak Company, directorate of research
- Hunter Associates Laboratory, Inc.
- Los Alamos Scientific Laboratory
- General Electric Corporate Research and Development
- Lawrence Livermore Laboratory
- General Telephone and Electronics Sylvania Lighting Center
- Cornell University department of chemistry
- California Institute of Technology department of physics
- Bell Laboratories, Murray Hill
- University of Rochester, department of physics and astronomy
- University of Wisconsin, Space Science and Engineering

An estimate of the opinion of the Heat Division Evaluation Panel on the quality of the thermometry program may be obtained from the following, quoted from the most recent report:

"The Panel believes that the thermometry program in the Heat Division, which includes the work in the Temperature Section and in the Cryogenic Physics Section as well as the Optical Pyrometry project in the Optical Radiation Section, is excellent. The objectives of the program are sound and they are appropriate. The staff working on thermometry are very competent and they are enthusiastic about their work. The accomplishments of the program in terms of publications and the thermometer developments made by the staff are significant in respect to both quantity and quality."

The Panel recommended that the program should be more heavily funded and staffed, but expressed an understanding of NBS limitations in that regard. Detailed discussions of some individual projects give considerable guidance to NBS in its efforts to maintain a lively, effective program.

The criteria by means of which NBS evaluates possible additions to its programs can be listed as follows:

- Relevance to the basic program
- Possible Scientific or Technical Advancement
- Adequacy of Resources (staff, equipment, and space)
- Available NBS Leadership.

In addition to the above criteria, work contemplated for other agencies must be of such a nature that NBS, its staff, or its facilities are uniquely suited for the project.

In the opinion of its line management, the major strength of the NBS thermometry program is that it has competent staff. Because of this fact, those areas which are treated at all receive intelligent attention. A second strength lies in the variety of the thermometry activities: The Heat Division staff performs calibrations, and basic and applied research in standard sensors; the Physical Chemistry Division staff studies thermometry as applied to differential thermal analysis and microcalorimetry; and the Center for Building Research studies thermometry applied to energy flow in construction materials.

The major weakness of the NBS Thermometry programs is that so many areas of thermometry are not under study at all. A second weakness is that there is too little interaction between the metrological thermometry in the Heat Division and the applied thermometrists working elsewhere in NBS.

The Evaluation Panel of the Heat Division generally supports these findings, offering high praise for the program as performed but regret at the thinness of its coverage of the field.

4.5 The Future of Thermometry at NBS

The considerations which have been treated in this study demonstrate a need for a number of activities for NBS thermometry, some along well-traveled paths and others in new directions.

a) The National Temperature Measurement System Study

In the first place, the assessment of the needs of the National Temperature Measurement System is clearly a valuable tool in directing NBS programs, and we believe that it should be a continuing process. Field visits, which currently occupy a great deal of effort (and not a little money) are an excellent source of information, much of which cannot be obtained in other ways. We see this activity diminishing in intensity within the next two years, however, as we become more knowledgeable regarding the National Temperature Measurement System. We expect then to continue the field visits at a reduced level.

As personal contacts become more firm and widespread, we expect to make greater use of telephone and correspondence as a means of maintaining liaison with current activities in facilities which we have already visited. This procedure will then form a substantial and continuing channel of communication.

A particularly important part of the study activity should be closer liaison between the Heat Division staff and the other NBS thermometry personnel. Where the programs require collaboration, it seems to take place in a satisfactory manner; however, lack of awareness and communication is apparent in many areas, and this problem is compounded by difficulties such as competition for external funding.

b) Calibrations

Secondly, our studies show a continuing need for a calibration capability in platinum, liquid, and thermocouple thermometers at the highest attainable levels of accuracy to maintain a uniform scale of temperature for both science and technology.

The construction of comparison facilities for calibration between fixed points and the design and installation of automatic bridging and data logging equipment can be expected to permit increased versatility in the calibration services. One potential feature of such services is an extended measurement assurance program which will permit NBS to evaluate selected calibration facilities, at their request, in the field.

As part of the calibration activities, the capability for fixed-point determinations is necessary. As part of this activity, the possibility of utilizing transitions in well-characterized solids will be examined. Such solid-state fixed points would be substantially easier to realize and to promulgate than most of those in existence at present.

c) The International Temperature Scale

Thirdly, work on the temperature scale should be continued. In particular, the gas thermometer investigation of the scale integrity should be pressed to an ultimate overlap with radiation thermometry.

The extension of the scale through the cryogenic range should be brought to fruition--if necessary, through NBS initiation of an international discussion to this end. The NBS acoustic thermometry has stimulated a similar effort at NPL in England, where acoustic thermometry results are being compared with others from gas and isotherm thermometry. The NBS noise and gamma-ray anisotropy thermometry may both overlap the acoustic thermometer range, offering a direct comparison of three fundamentally different thermometers. The superconductive fixed point program may provide, in addition to the five points presently existing between 7.2 K and 0.5 K, further points at 18 K, 13 K, 0.1 K, and 0.2 K; an evaluation of these as potential defining points on the cryogenic scale should be pressed. The generation of a convenient, accurate, and reliable thermometer for transmitting the cryogenic scale to the cryogenics industry is a vital part of this program, as well. The nuclear magnetic resonance thermometer offers not only an alternative cryogenic sensor, but a means of following current research trends toward ever-lower temperatures.

Another area of temperature scale research involves the convenient, accurate measurement of temperatures in the 600 - 2000 °C range. At present, neither thermocouple nor resistance thermometry is completely satisfactory in this range, and as industrial needs expand, NBS clearly can provide substantial help by continuing to work in this area.

Finally, NBS should respond to the various thermometry needs which have become evident in the National Temperature Measurement System study. We can assume that only a small fraction of the total problems have been discovered up to the present time, and that others will demand attention as the study continues.

d) Medical Thermometry

In the area of Medical Thermometry, work has begun on the characterization of thermistors and of commercial platinum resistance thermometers. In addition, B. W. Mangum and S. D. Wood are actively building, in collaboration with the medical community, with the Food and Drug Administration, and with the Bureau of Radiological Health, a further technical base for medical thermometry. The expected end product is standardization of medical thermometry with a consequent dramatic improvement in the quality and uniformity of patient care in the U.S.

e) Needs for Improved Thermometry in Energy

Major changes are occurring in the worldwide production and use of energy. The current crisis in oil-based energy has propelled the U.S. into careful studies of alternative sources. Most of these studies indicate that new extensions of existing thermometer capabilities will be necessary if the U.S. is to generate appreciable new sources of energy.

Take, as an example, increased utilization of nuclear fission reactor power. Present technology, while virtually free of serious accidents, still is in such a state that remote siting of power reactors offers the best means of widespread acceptance. In turn, remote siting places heavy demands on the capability for low-loss transfer of electric power over long distances and into major cities; in our opinion, this problem calls for the introduction in large quantity of superconductive power transmission lines. These lines, composed of a central conductor coaxial with a flowing coolant and an enclosing return conductor, are of such tremendous current-carrying capacity that a superconducting gaseous-helium-cooled cable the size of a man's arm can carry as much power as some twenty high voltage towers can support. They require cryogenic installation and, probably, underground siting. One cable, however, is expected to supply so much power that, for example, Brookhaven National Laboratory expects that its coming experimental switchover to 100% superconducting power cable will not even provide test data on the ultimate capacity of a single cable.

The reader should note well with respect to superconductive power transmission, that the entire cable except for its outer shield will be existing at a temperature completely beyond the range of the present International Scale!

Superconductive power transmission figures heavily too, in our opinion, in the intensive use of solar and geothermal power. These sources do not occur near the great cities whose power needs they may fulfill, so that low-loss, high capacity, long lines will be a necessity for their use.

Field calibration of accurate thermometers used for lifetime prediction for geothermal sources will become quite important, in our opinion. Such on-site calibration will go far to break the "calibration chain" effects of long time delays in calibration and concomitant loss of instrumental accuracy.

In the Energy Research and Development Administration, an Assistant Administrator for Conservation has been formed. Success, for this group, must be measured in terms of thermodynamics. A whole new order of thermometric accuracy, convenience, and persistence must be considered if its efforts are to be effective and appreciated.

Household energy use as well may call for thermometric improvement. The growing trend to condominium and apartment dwellings dictate consideration of central power sources for heat and light, but how to monitor energy consumption?

In the area of thermometry in energy, we are investigating the employment of thermometry as one tool in enhancing the efficiency of present power production facilities and in effective safety and control of fast breeder reactor plants. In addition we are probing the thermometric aspects of the thermocline oceanographic heat pump power generation and that of geothermal, controlled thermonuclear reactor, and solar power plants. It should be noted, however, that the scientific problems appear to be by far the simplest feature of increasing the efficiency of existing power facilities. Economic and political considerations here ("who pays for it?") are not trivial.

f) Industrial Standards

In the area of industrial standards, we will undertake basically a liaison role which has two tasks. First, catalog the standardization activities of the various groups which were noted in Section 2, and second, communicate directly with the individual industries of Section 2 and with the "standards industry" so that they *can* cooperate in writing standards if they so desire. The next few years are certain to be critical ones for U.S. industry because of the competition of foreign manufacturers, and part of the problem will arise through international standardization. NBS participation in the standardization process by providing technical advice and effective liaison can benefit both the American consumer and U.S. industry.

A continuing and challenging problem area exists in trying to promote the production of higher quality, safer, and more internationally competitive products through industrial thermometry. This is an activity which concerns primarily the group noted in Section 2.

Both of these tasks are difficult. Although our experience to date may be atypical, we found that many commodity manufacturers are interested in thermometry primarily as it relates to the efficiency of manufacture; they show little interest in thermometry applied to the ability of the product to perform its function or to its durability. The principal reason given for this attitude is an economic one, and the challenge is to provide the means by which the economic question can be overcome. Tools which can be used in this effort include a reference service for thermometry expressly intended and publicized to offer technical information (on sensors and measurement techniques) and locator information (on geographic availability of calibration and engineering laboratories) to help eliminate that portion of thermometry problems which arises through a lack of awareness of existing technology and a well-planned Measurement Assurance or Measurement System Calibration program to sample thermometry competence in "willing", selected facilities.

5. SUMMARY AND CONCLUSIONS

To summarize the state of the National Temperature Measurement System is to summarize the state of the U.S. economy, its science and its technology. Thermometry is literally an all-prevading activity.

In this Study we have attempted to portray the structure of the National Temperature Measurement System, beginning with the most basic concepts, noting the sensors and other thermometry tools, and sketching the composition of the major developers and users of thermometry. We have discussed the technological and economic aspects of thermometry as they relate to the life of the average American. Finally we have presented a picture of the thermometry activities of the NBS, attempting to show the many ways in which the Bureau provides technical resources to help the nation to progress in thermometry.

We conclude that temperature measurement and control in the U.S. is sufficiently precise and accurate to accomplish its stated objective. Areas which are deficient (medicine, new energy sources) are areas which involve new technology or in which no clear mechanism exists to focus on problems and to eliminate them.

Areas in which we see particular needs developing over the next few years are:

- High-temperature thermometry measurement and control
- Thermometry in cryogenics
- Fast-responding sensors
- Time dependent measurements
- Measurements in hostile environments
- Calibration of measurement systems
- Calibration of reduced-accuracy thermometers
- New working relations between national and international standardization groups

Building on the foundation of this study, NBS thermometry must maintain a lively interest in the activities of groups throughout the National Temperature Measurement System and continually evaluate and assess the priorities of potential NBS programs in the light of the needs of the entire System.

6. ACKNOWLEDGEMENTS

As noted at the outset, this study was written by a single individual. However, most of the members of NBS Sections 221.03 and 221.11 have contributed directly to the study, and many people, including H. H. Plumb, G. T. Furukawa, R. J. Soulen, G. W. Burns, W. S. Hurst, H. Marshak, and B. W. Mangum in addition to the author, have visited various facilities on its behalf. The assistance of all of these people is gratefully acknowledged.

7. REFERENCES

Section 1. Introduction

[1] Private communication, colleague at NBS.

[2] The National Measurement System study is a collection of over twenty individual "micro studies" of activities in the Institute for Basic Standards, U. S. NBS.

[3] U. S. Department of Commerce Organization Order 30-2B.

Section 2. Structure of the System

[1] A short history of thermometry can be found in an article by R. B. Lindsay in Vol. 3, Part 1, p. 3 of "Temperature, Its Measurement and Control in Science and Industry" edited by C. M. Herzfeld, Reinhold, N. Y., 1962.

[2] H. T. Wenzel (then Chief, Pyrometry Section, NBS) in the lead article in Vol. 1 of "Temperature, Its Measurement and Control", Reinhold, N. Y., 1941.

[3] W. Thomson, Phil. Mag. 33, 313 (1848).

[4] The word "clearly" here may have been somewhat optimistic, although it seems clear to *us*. Reference 2 and an article by C. M. Herzfeld on p. 41 of the volume referred to in reference 1 both discuss this point.

[5] Even today, neither thermodynamic thermometry nor any fixed points other than the triple point and the boiling point of water are in common use; nevertheless, the standard instruments used in practical thermometry reproduce the most heavily-used portion of the scale within about 100 ppm of thermodynamic temperatures.

[6] G. K. Burgess, J. Res. NBS, 1, 635 (1928).

[7] The scale is described in an article by J. A. Hall of NPL on p. 115 of Vol. 2 of "Temperature, Its Measurement and Control in Science and Industry, Reinhold, N. Y., 1955.

[8] The chief reason for the separate definitions, according to Hall (Ref. 7), is that whereas the 100 °C interval between the ITS defining points was known to ±.001 °C (thus the ITS degree Celsius was reproducible to ±10 ppm) the thermodynamic accuracy of the triple point was ±.01 °K so that the degree Kelvin could be known only to ±30 ppm.

[9] "The Committee", Metrologia 5, 35 (1969).

[10] This adjective was added in 1960.

[11] In fact one such adjustment has already been suggested by L. A. Guildner of NBS, who points out that *his* gas thermometer only reads 99.97 °C at the boiling point of water. This and other NBS contributions to current thermometry are discussed in Section 4.

[12] Metrologia 5, 35 (1969).

[13] At NBS, for example, only five of these exist.

[14] International Standards Organization "Memento 1972". Copies of this and other documents relating to ISO might be obtained from the ISO at 1, rue de Varembe', 1211 Geneve 20, Switzerland. The same address applies for the IEC.

[15] The NBS Technical News Bulletin, February 1973, contains on p. 47 a short discussion of the O.I.M.L. and the beginning of U.S. participation therein.

[16] The pre-1970 history of ANSI can be traced through "The Magazine of Standards" articles in January 1967, January 1968, September 1968, November, 1968, April 1969, and October 1969. Presently, ANSI activities are described in the "ANSI Reporter", published biweekly by ANSI, 1430 Broadway, New York 10018.

[17] ASTM, 1916 Race Street, Philadelphia, 19103, publishes the "ASTM Standardization News", a monthly magazine which discusses its affairs in concise but informal fashion.

[18] ASTM Standardization News, February 1973, p. 4.

[19] Ibid., p. 32.

[20] J. A. Beattie, Vol. 2, p. 63, of "Temperature", Reinhold, (1955).

[21] W. D. Huston, Vol. 3, Part 2, p. 949 of "Temperature", Reinhold, (1962).

[22] E. F. Moeller, on p. 162 of the volume cited in reference 1, discusses Callendar's work in the general context of precision resistance thermometry.

[23] We shall discuss further, in Section 4, the paper by J. P. Evans and S. D. Wood, Metrologia, 7, 108 (1971).

[24] G. T. Furukawa, Vol. 3, Part 2, p. 320 of "Temperature", Reinhold, 1962.

[25] A comprehensive summary of the principles and practice of thermoelectric thermometry appear in Section 1 of Vol. 3, Part 2 of "Temperature" Reinhold, 1962.

[26] ASTM Handbook of Standards, Part 30, 1972.

[27] The Thomas Register (Thomas Publishing Company, 461 Eighth Avenue, N. Y. 10001) is a good source of information on commercial products and manufacturers.

[28] One instrument manufacturer estimates privately that 40-45% of all sales are concerned with temperature-control apparatus.

[29] See the discussion in Sections 2.2.2.1 and 2.5.

[30] See Section 2.2.2.1 and figure 2.2F for references to these various sensors.

[31] This is a control thermostat manufactured specifically for household use.

[32] It is not unusual for thermistors to vary in resistance by a factor 5 or 10 over a 100 °C interval.

[33] Private communication, thermistor manufacturer.

[34] Industrial Research, June 1973, p. 64.

[35] Many of the manufacturers listed in reference 27 fabricate these sensors.

[36] K. R. Carr, Vol. 4, Part 2 of "Temperature" 1972, p. 971. Dr. Carr has privately told the author of some additional work on this topic.

[37] Commercial ad in Research/Development, November 1973, p. 37.

[38] Private communication, thermometer manufacturer.

[39] The variation in the readings found on "drug store thermometers", often as much as several degrees Fahrenheit, is probably a consequence of economics. We shall see.

[40] Artronix Instrumentation, in the December 1973, Physics Today.

[41] Private communication.

[42] Private communication.

[43] Catalog of NBS Standard Reference Materials, NBS Special Publication 260, June 1975, p. 51.

[44] Preparation and Use of Superconductive Fixed Point Devices, SRM 767, NBS Special Publication 260-44, December 1972.

[45] Dr. K. Churney. Private communication.

[46] See J. Terrien, Metrologia 1, 15 (1965).

[47] "Men and Measurements - United States Army Metrology and Calibration Center", prepared by the Program Management and Administrative Office of the U. S. Army Metrology and Calibration Center, Redstone Arsenal, Alabama 35809, April 1970.

[48] Ibid., p. 98.

[49] "A Directory of Standards Laboratories" can be obtained from NCSL Directory Committee, c/o NBS 200.01, Washington, D. C. 20234.

[50] Comment by the president of a thermometer company, during a visit by an NBS staff member.

[51] Private communication, via the 28th Annual Calorimetry Conference; 13-15 June 1973 at Worcester, Massachusetts.

[52] Electronics, October 1973, p. 88.

[53] Private communication.

[54] Private communication.

[55] Commerce Today, April 30, 1973, pp. 30-32.

[56] Discussions with AEC and ORNL personnel.

[57] Private communication, M. Smith, LASL.

[58] W. Vannah (of Foxboro Corp.) in NAS-NRC Physics Instrumentation Report, 1971.

[59] J. G. McMillan, R. H. Pamperin, SAE Congress, Detroit, January 1972.

[60] Private communication, industrial scientist.

[61] T. Berlincourt, in NAS/NRC Physics Instrumentation Report, 1971; private communication, H. J. Kostkowski, Chief, Optical Radiation Section.

Section 3

[1] J. H. V. Brown and D. J. Lowell, IEEE Transactions in Biomedical Engineering, Vol. BME-19, 331 (1972).

[2] R. S. Melville, Chemical Instrumentation 4, 63 (1972).

[3] Mal Schechter, Lab World, May 1973, p. 26.

[4] Nathan Gochman, IMR Special Colloquium, NBS, 23 March, 1973.

[5] Wall Street Journal, 17 July, 1973.

[6] Private discussion with the chief of an experimental automotive research laboratory, 1973.

[7] F. B. Dent, Commerce Today, August 6, 1973, p. 25.

[8] Deborah Shapley, Science, 182, p. 732 (1973).

[9] P. C. White, Science, 182, 23 November 1973.

[10] P. G. Hansel, Industrial Research/Development, p. 8, July 1973.

[11] NBS Technical News Bulletin, January 1973.

[12] Brooklyn Thermometer Co., Inc., $60; AMI-Therm., $15 and $20.

[13] Nuclear News, p. 39, September 1973.

[14] Conversations with the Directorate of Reactor Development, AEC; with the Instrumentation and Controls Division, AEC; and with a representative of Bechtel Corporation, nuclear engineers.

[15] Nuclear News, September 1973, p. 53.

[16] 1973 Press Handbook, TVA.

[17] An example of this activity in thermal conductivity is Y. S. Touloukian, R. W. Powell, C. Y. Ho, and P. G. Klemens, Thermophysical Properties Research Center Data Series, 1, IFI/ Plenum Data Corp., 1970.

[18] Even here, NBS enters the picture. Through the National Standards Reference Data Service, NBS fosters a large proportion of this analysis.

Section 4

[1] G. K. Burgess, J. Res. NBS 1, 635 (1928).

[2] "Temperature", Vol. 1, 1941, Reinhold, New York.

[3] "Temperature", Vol. 2, 1955, Reinhold, New York.

[4] "Precision Measurement and Calibration-Temperature", NBS Special Publication 300, Vol. 2, 1968.

[5] "Precision Measurement and Calibration-Heat", NBS Special Publication 300, Vol. 6, 1970.

[6] "Temperature", Vol. 4, 1972, Instrument Society of America, Pittsburgh.

[7] "Temperature Section Activity Summary, 1974" J. F. Schooley, ed. NBS Technical Note 869, June 1975.

[8] The International Practical Temperature Scale of 1968", Metrologia 5, 35 (1969).

[9] The minutes are published (in French) by the International Bureau of Weights and Measures, Pavillon de Breteuil, F 92310, Sèvres, France.

[10] J. F. Schooley, R. J. Soulen, Jr., and G. A. Evans, Jr., NBS Special Publication 260-44, December 1972, and R. J. Soulen, Jr., J. F. Schooley, and G. A. Evans, Jr., Rev. Sci. Instr. 44, 1537 (1973).

[11] NBS Tech. News Bulletin, February 1973, p. 47.

[12] Sad to say, OIML approved the draft recommendation over the U. S. objections! Therefore, the end of this particular story will come only after the U. S. has attempted to amend the draft.

[13] NBS Tech. News Bulletin, May 1973.

[14] Commerce Today, 6 August 1973, p. 10.

[15] D. Burch, NBS Standard, 5 December 1973, p. 5.

[16] NBS Dimensions, August 1973, p. 181.

[17] J. Cohen, S. Edelman, and C. Vezzetti, Nature Phys. Sc. 233, 12 (1971).

[18] NBS Tech. News Bulletin, December 1972, p. 277.

[19] A. Cezairliyan, J. Res. NBS 77A, 45 (1973).

[20] A. Cezairliyan, J. Res. NBS 77A, 333 (1973).

[21] E. J. Prosen and R. N. Goldberg, NBS Interim Report 73-180, April 1973.

APPENDIX A. METHODOLOGY OF THE STUDY

The study of the National Temperature Measurement System was accomplished by utilizing several sources of information:

. The literature of thermometry, especially useful because periodic symposia on "Temperature, Its Measurement and Control in Science and Industry", for years held with NBS sponsorship, provides a detailed summary of active areas of thermometry. The journal Metrologia, trade association periodicals, and the scientific and engineering literature all were methodically consulted in order to develop a comprehensive overview of the state of thermometry in the U. S.

. Personal knowledge on the part of NBS staff members provided individual insights into the strengths and needs of U. S. thermometry. These were augmented by a series of visits to less well--known areas of thermometry applications in order to build a collection of personal contacts which will continue to provide information through telephone and written communication.

. Participation in scientific and technical meetings, as well as the delivery of talks, instructional seminars, and tours, provided up-to-date information on areas where thermometry is advancing, where it is stymied for lack of fundamental research results, and areas in which future efforts are most likely to be rewarding.

. Economic data were obtained from personal contacts in government and industry.

The rough impressions of many staff members were integrated to build a picture of the System, in an early draft of the study, and later efforts focused on areas where uncertainty remained. Successive visits, telephone discussions and correspondence generally served to bring out the requisite information, so that we did not resort to formal polling techniques.

APPENDIX B. SUMMARY OF BACKGROUND DOCUMENTS

1. "Temperature, Its Measurement and Control in Science and Industry", Vol. 4, H. H. Plumb, Editor-in-Chief, Instrument Society of America, Pittsburgh, 1972. This three-part volume is an essential reference for understanding the position of thermometry at the present time. A significant history of the International Practical Temperature Scale by H. Preston-Thomas, of the National Research Council Laboratories in Ottawa, opens the volume, and the volume covers the topics:
   - Temperature Scales and Fixed Points
   - Radiation Thermometry
   - Resistance Thermometry
   - Magnetic and Quantum Thermometry
   - Temperature Control and Calibration
   - Bridges and Potentiometers
   - Thermoelectric Thermometry
   - Biology and Medicine
   - Geophysical and Astrophysical Thermometry
2. "The International Practical Temperature Scale of 1968" Metrologia 5 35 (1969). This document is the defining text for the current International Temperature Scale. It contains the assigned values and definitions of the scale fixed points and the descriptions of the standard interpolating sensors.
3. "Standard Industrial Classification Manual", Office of Management and Budget. The SIC code defines industries in accordance with the composition and structure of the economy and covers the entire field of economic activities.
4. "U. S. Industrial Outlook Series" Domestic and International Business Administration, U. S. Department of Commerce. This series of reports is oriented toward the future economic patterns of the U. S. Detailed analysis of some 200 industries, covering about 85% of the total value of shipments in the U. S., are presented with projections to 1980.
5. "Annual Survey of Manufacturers Series" Social and Economic Statistics Administration, Bureau of the Census, U. S. Department of Commerce. This series contains reports of product shipments for perhaps 1000 classes of manufactured products. It is a very useful tool for the economic examination of particular industries.
6. "The U. S. Government Organization Manual". General Services Administration. A very useful guidebook to the Federal bureaucracy

APPENDIX B. SUMMARY OF BACKGROUND DOCUMENTS

7. "The Thomas Guide to Manufacturers" (Thomas Publishing Company, N.Y. 10001). A comprehensive guide to products and organizations of U. S. industry.
8. "A Directory of Standards Laboratories", Prepared by the National Conference of Standards Laboratories. This directory serves as a "classified index" of U. S. standards laboratories.

APPENDIX C. RP 22, NBS Journal of Research, Vol. 1, 635 (1928)

THE INTERNATIONAL TEMPERATURE SCALE, George K. Burgess

In 1911, the directors of the national laboratories of Germany, Great Britain, and the United States agreed to undertake the unification of the temperature scales in use in their respective countries. This endeavor was approved formally in 1913 by the Fifth General Conference on Weights and Measures, and in 1921 the Sixth General Conference voted to expand the field of activities of the International Committee and International Bureau by including physical constants, such as standard temperatures, and the coordination of results obtained in other institutions. This action was duly ratified by the several governments adhering to the conference.

Finally, in 1927, the Seventh General Conference, representing 31 nations, on the recommendation of the three laboratories above mentioned, which had consulted with the Leiden Cryogenic Laboratory as to low temperatures, adopted unanimously the following resolution, proposed by the International Committee of Weights and Measures:

Le Comité, reconnaissant l'importance pratique de la représentation d'une échelle thermométrique internationale, recommande à la Conférence d'accepter, à titre provisoire, les repères de température, les formules d'interpolation et les méthodes de mesure proposés d'un commun accord par les trois laboratories nationaux d'Allemagne, des États-Unis d'Amérique, et de Grande-Bretagne.

Le Comité recommande aussi que le texte annexé soit maintenu a l'étude dans le programme des Conférences spéciales de Thermométrie qui seront tenues sous ses auspices.

The English text is as follows:

TEXT CONCERNING THE ADOPTION OF AN INTERNATIONAL TEMPERATURE SCALE SUBMITTED FOR DISCUSSION BY THE BUREAU OF STANDARDS, NATIONAL PHYSICAL LABORATORY, AND PHYSIKALISCH-TECHNISCHE REICHSANSTALT

INTRODUCTION

The experience of the Bureau of Standards, as of the National Physical Laboratory and of the Reichsanstalt, has for many years past indicated the necessity, for industrial purposes, of international agreement on a scale of temperatures ranging from that of liquid oxygen to that of luminous incandescent bodies. As a result of discussion extending over a considerable period, agreement has been reached by the three laboratories, subject to possible minor drafting amendments on the attached specification for a practical scale, as affording a satisfactory basis on which uniformity in certification of temperature measurements for industrial purposes may be maintained.

It is to be understood that this proposal does not purport to replace the absolute temperature scale which it is recommended should be adopted, on principle, by the International Conference on Weights and Measures. It is intended merely to represent this scale in a practical manner with sufficient accuracy to serve the every day needs of the laboratories for the purpose of industrial certifications, and is to be regarded as susceptible of revision and amendment as improved and more accurate methods of measurement are evolved.

It is anticipated that this scale will shortly be adopted by the three laboratories for the purposes indicated, and the attached draft is presented to the conference for consideration, with the recommendation that it should be officially adopted with such amendments, if any, as may be agreed on, as the best practical realization at the present time of the ideal thermometric scale.

Part I. DEFINITION OF THE INTERNATIONAL TEMPERATURE SCALE

1. The Thermodynamic Centigrade Scale, on which the temperature of melting ice, and the temperature of condensing water vapor, both under the pressure of one standard atmosphere, are numbered 0° and 100°, respectively, is recognized as the fundamental scale to which all temperature measurements should ultimately be referable.

2. The experimental difficulties incident to the practical realization of the thermodynamic scale have been expedient to adopt for international use a practical scale designated as the International Temperature Scale. This scale conforms with the thermodynamic scale as closely as is possible with present knowledge, and is designed to be definite, conveniently and

accurately reproducible, and to provide means for uniquely determining any temperature within the range of the scale, thus promoting uniformity in numerical statements of temperature.

3. Temperatures on the international scale will ordinarily be designated as "°C", but may be designated as "°C.(Int.)" if it is desired to emphasize the fact that this scale is being used.

4. The International Temperature Scale is based upon a number of fixed and reproducible equilibrium temperatures to which numerical values are assigned and upon the indications of interpolation instruments calibrated according to a specified procedure at the fixed temperatures.

5. The basic fixed points and the numerical values assigned to them for the pressure of one standard atmosphere are given in the following table, together with formulas which represent the temperature (t_p), as a function of vapor pressure (p) over the range 680 to 780 mm of mercury.

6. Basic fixed points of the International Temperature Scale-- °C

(a) Temperature of equilibrium between liquid and gaseous oxygen at the pressure of one standard atmosphere (oxygen point)--- -182.97

$$t_p = t_{760} +0.0126\ (p-760) -0.0000065\ (p-760)^2$$

(b) Temperature of equilibrium between ice and air-saturated water at normal atmospheric pressure (ice point)--- 0.000

(c) Temperature of equilibrium between liquid water and its vapor at the pressure of one standard atmosphere (steam point) ------ 100.000

$$t_p = t_{760} + 0.0367\ (p-760) -0.000023\ (p-760)^2$$

(d) Temperature of equilibrium between liquid sulphur and its vapor at the pressure of one standard atmosphere (sulphur point)----- 444.60

$$t_p = t_{760} + 0.0909\ (p-760) - 0.000048\ (p-760)^2$$

(e) Temperature of equilibrium between solid silver and liquid silver at normal atmospheric pressure (silver point)------ 960.5

(f) Temperature of equilibrium between solid gold and liquid gold at normal atmospheric pressure (gold point)----- 1063

Standard atmospheric pressure is defined as the pressure due to a column of mercury 760 mm high, having a mass of 13.5951 g/cm^3, subject to a gravitational acceleration of 980.665 cm/sec^2 and is equal to 1,013,250 dynes/cm^2.

It is an essential feature of a practical scale of temperature that definite numerical values shall be assigned to such fixed points as are chosen. It should be noted, however, that the last decimal place given for each of the values in the table is significant only as regards the degree of reproducibility of that fixed point on the International Temperature Scale. It is not understood that the values are necessarily known on the Thermodynamic Centigrade Scale to the corresponding degree of accuracy.

7. The means available for interpolation lead to a division of the scale into four parts.

(a) From the ice point to 660 °C the temperature t is deduced from the resistance R_t of a standard platinum resistance thermometer by means of the formula

$$R_t = R_o\ (1 + At + Bt^2).$$

The constants R_o, A, and B of this formula are to be determined by calibration at the ice, steam, and sulphur points, respectively.

The purity and physical condition of the platinum of which the thermometer is made should be such that the ratio R_t/R_o shall not be less than 1.390 for $t = 100°$ and 2.645 for $t = 444.6°$.

(b) From -190° to the ice point, the temperature t is deduced from the resistance R_t of a standard platinum resistance thermometer by means of the formula

$$R_t = R_o\ [1 + At + Bt^2 + C\ (t-100)t^3].$$

The constants R_o, A, and B are to be determined as specified above, and the additional constant C is determined by calibration at the oxygen point.

The standard thermometer for use below 0° C must, in addition, have a ratio R_t/R_o less than 0.250 for $t = -183°$.

(c) From 660 °C to the gold point, the temperature t is deduced from the electromotive force e of a standard platinum vs platinum-rhodium thermocouple, one junction of which is kept at a constant temperature of 0 °C while the other is at the temperature t defined by the formula

$$e = a + bt + ct^2.$$

The constants a, b, and c are to be determined by calibration at the freezing point of antimony, and at the silver and gold points.

(d) Above the gold point the temperature t is determined by means of the intensity J_2 of monochromatic visible radiation of wavelength λ cm, emitted by a black body at the temperature t_2, to the intensity J_1 or radiation of the same wavelength emitted by a black body at the gold point, by means of the formula

$$\log_e \frac{J_2}{J_1} = \frac{c_2}{\lambda}\left[\frac{1}{1,336} - \frac{1}{(t + 273)}\right]$$

The constant c_2 is taken as 1.432 cm degrees. The equation is valid if (t + 273) is less than 0.3 cm degrees.

Part II. RECOMMENDED EXPERIMENTAL PROCEDURE

1. OXYGEN

The temperature of equilibrium of liquid and gaseous oxygen has been best realized experimentally by the static method, the oxygen vapor-pressure thermometer being compared with the thermometer to be standardized in a suitable low temperature bath.

2. ICE

The temperature of melting ice is realized experimentally as the temperature at which pure, finely divided ice is in equilibrium with pure, air-saturated water under standard atmospheric pressure. The effect of increased pressure is to lower the freezing point to the extnt 0.007 °C per atmosphere.

3. STEAM

The temperature of condensing water vapor is realized experimentally by the use of a hypsometer so constructed as to avoid superheat of the vapor around the thermometer, or contamination with air or other impurities. If the desired conditions have been attained, the observed temperature should be independent of the rate of heat supply to the boiler, except as this may affect the pressure within the hypsometer, and of the length of time the hypsometer has been in operation.

4. SULPHUR

For the purpose of standardizing resistance thermometers, the temperature of condensing sulphur vapor is realized by adherence to the following specifications relating to boiling apparatus, purity of sulphur, radiation shield, and procedure.

The boiling-tube is of glass, fused silica, or similar material, and has an internal diameter of not less than 4 or more than 6 cm. The vapor column must be sufficiently long that the bottom of the radiation shield is not less than 6 cm below the top of the heat insulating material surrounding the tube. Electric heating is preferable, although gas may be used, but the source of heat and all good conducting material in contact with it must terminate at least 4 cm below the free surface of the liquid sulphur. Above the source of heat the tube is surrounded with insulating material. Any device used to close the end of the tube must allow a free opening for equalization of pressure.

The sulphur should contain not over 0.02 percent of impurities. Selenium is the impurity most likely to be present in quantities sufficient to affect the temperature of the boiling point.

The radiation shield is cylindrical and open at the lower end, and is provided with a conical portion at the top, to fit closely to the protecting tube of the thermometer. The cylindrical part is 1.5 to 2.5 cm larger in diameter than the protecting tube of the thermometer and at least 1 cm smaller in diameter than the inside of the boiling tube. The cylinder should extend at least 1.5 cm beyond each end of the thermometer coil. There should be ample opening at the top of the cylindrical and below the conical portion to permit free circulation of vapor. The inner surface of the shield should be a poor reflector. The shield may be made of sheet metal, graphite, etc.

In standardizing a thermometer the sulphur is heated to boiling and the heating so regulated that the condensation line is at least 1 cm above the top of the insulating material. The thermometer with its radiation shield is inserted in the vapor, and when the line of condensation again reaches its former level simultaneous observations of resistance and barometric pressure are made. In all cases care should be taken to prove that the temperature is independent of vertical displacements of the thermometer and shield.

5. SILVER AND GOLD

For standardizing a thermocouple, the metal to be used at its freezing point is contained in a crucible of pure graphite, refractory porcelain, or other material which will not react with the metal so as to contaminate it to an appreciable extent.

Silver must be protected from access of oxygen while heated.

The crucible and metal are placed in an electric furnace capable of heating the contents to a uniform temperature.

The metal is melted and brought to a uniform temperature a few degrees above its melting point, then allowed to cool slowly with the thermocouple immersed in it as described in the next paragraph.

The thermocouple, mounted in a porcelain tube with porcelain insulators separating the two wires, is immersed in the molten metal through a hole in the center of the crucible cover. The depth of immersion should be such that during the period of freezing the thermocouple can be lowered or raised at least 1 cm from its normal position without altering the indicated emf by as much as 1 microvolt. During freezing, the emf should remain constant within 1 microvolt for a period of at least five minutes.

As an alternative to displacing the couple, as a means of testing the absence of the influence of external conditions upon the observed temperature, both freezing and melting points may be observed and if these do not differ by more than 2 microvolts, the observed freezing point may be considered satisfactory.

6. THE STANDARD PLATINUM RESISTANCE THERMOMETER

The diameter of the wire should not be smaller than 0.05 or larger than 0.2 mm.

The platinum wire of the thermometer must be so mounted as to be subject to the minimum of mechanical constraint, so that dimensional changes accompanying changes of temperature may result in a minimum of mechanical strain being imposed upon the platinum.

The design of the thermometer should be such that the portion, the resistance of which is measured, shall consist only of platinum, and shall be at the uniform temperature which is to be measured. This may be accomplished by either of the accepted systems of current and potential, or compensating leads.

After completion, the thermometer should be annealed at a temperature of at least 660°.

7. THE STANDARD THERMOCOUPLE

The platinum of the standard couple shall be of such purity that the ratio R_t/R_o is initially not less than 1.390 for $t = 100°$. The alloy is to consist of 90 percent platinum with 10 percent rhodium. The completed thermocouple must develop an electromotive force, when one junction is at 0° and the other at the freezing point of gold, not less than 10,200 nor more than 10,400 international microvolts. The diameter of the wires used for standard thermocouples should lie between the values 0.35 and 0.65 mm.

The freezing point of antimony, specified for the standardization of the thermocouple, lies within the range of 0° to 660° where the international scale is fixed by the indications of the standard resistance thermometer, and the numerical value of this temperature is therefore to be determined with the resistance thermometer. In the appendix the result of such determinations is given as 630.5°, but the temperature of any particular lot of antimony which is to be used for standardizing the thermocouple is to be determined with a standard resistance thermometer.

The procedure to be followed in using the freezing point of antimony as a fixed temperature is substantially the same as that specified for silver. Antimony has a marked tendency to undercool before freezing. The undercooling will not be excessive if the metal is heated only a few degrees above its melting point and if the liquid metal is stirred. During freezing the temperature should remain constant within 0.1° for a period of at least five minutes.

8. SECONDARY POINTS

In addition to the basic fixed points, the temperatures of a number of other points are available and may be used in the calibration of secondary temperature measuring instruments. These points and their temperatures on the international scale are listed below. The temperatures given are those corresponding to a pressure of one standard atmosphere. The formulas for the variation of vapor pressure with temperature are valid for the range from 680 to 780 mm.

	°C
Temperature of equilibrium between solid and gaseous carbon dioxide--	-78.5

$$t_p = t_{760} + 0.1443(t_p + 273.2)\log_{10}(p/760)$$

Temperature of freezing mercury	-38.87
Temperature of transition of sodium sulphate ---	32.38
Temperature of condensing napthalene vapor----	217.96

$$t_p = t_{760} + 0.208(t_p + 273.2)\log_{10}(p/760)$$

Temperature of freezing tin-----	231.85
Temperature of condensing benzophenone vapor-----	305.9

$$t_p = t_{760} + 0.194(t_p + 273.2)\log_{10}(p/760)$$

Temperature freezing cadmium---	320.9
Temperature of freezing lead---	327.3
Temperature of freezing zinc---	419.45
Temperature of freezing antimony--	630.5
Temperature of freezing copper in a reducing atmosphere----	1,083
Temperature of freezing palladium	1,555
Temperature of melting tungsten	3,400

The Bureau of Standards, therefore, in common with the other national laboratories, will use until further notice in its scientific work and for the calibration of instruments, the standard temperatures, interpolation formulas, and methods of measurement as laid down above by the General Conference of Weights and Measures on October 4, 1927. It is recommended that scientific workers elsewhere conform to the International Temperature Scale as above set forth.

It is expected that international thermometric conferences will be called, as occasion requires, by the International Committee on Weights and Measures, so that this temperature scale may be revised as the need arises.

Washington, September 12, 1928.

APPENDIX D.
NBS Participation in Voluntary Standards Bodies' Thermometry Activities

1. R. P. Hudson, Chief 221: U. S. representative to 10th CCPM Advisory Committee on Thermometry session; General Chairman of 5th Temperature Symposium, and Chairman of CCT Working Group 5.
2. H. H. Plumb, Program Chairman of 5th Temperature Symposium and Editor-in-Chief of the Proceedings; Member Working Group 1 of CGPM Advisory Committee on Thermometry; Member NBS Commodity Standards Committee; Member ASTM Committee E-20; Member, ISA.
3. L. A. Guildner, 221.11: Member, Working Group 3 of CGPM Advisory Committee on Thermometry.
4. G. W. Burns, 221.11: Member, ASTM Committee E-20; Member ANSI Committee C-96; Member, ISA.
5. G. T. Armstrong, Chief 316.02: Member ASTM Committee E-20.
6. W. S. Hurst, 221.11: Member ANSI Committee C-96; Member, ISA.
7. J. A. Wise, 221.11: Member ASTM Committee E-20.
8. C. A. Douglas 232.11: Member, IES.
9. J. P. Evans, 221.11: Member, ISA.
10. R. K. Kirby, 312.06: Member ASTM Committee E-1.
11. F. R. Kotter, 211.06: Member ASTM Committee on Temperature in Power Systems.
12. R. H. Kropschott, 275.00: Member ANSI Committee C-16.
13. L. R. Moffitt, 272.00: Member ANSI Committee C-105.
14. F. J. Powell,462.00: Member ASTM Committee on Heat Transfer.
15. R. L. Powell, 275.00: Member ASTM Committee E-20.
16. Richard Raybold, 425.03: Chairman, Instrumentation Subcommittee, Oceanographic Measurements Society.
17. J. L. Riddle, 221.11: Member, ASTM Committee E-20.
18. T. B. Douglas, 425.03: Member ASTM Committee E-20.
19. J. F. Schooley, Chief 221.11: Member ASTM Committee E-20.

APPENDIX E. RESISTANCE THERMOMETERS

1. Doped germanium. (References: S. A. Friedberg, p. 359, Vol. 2, "Temperature", Reinhold (1955). J. E. Kunzler, T. H. Geballe, and G. W. Hull, Jr., p. 391, Part 1, Vol. 3 "Temperature, Its Measurement and Control in Science and Industry", Reinhold, N. Y. (1962); W. R. G. Kemp, J. G. Collins, C. P. Pickup, R. Muijlwijk, p. 85, Part 1, Vol. 4 "Temperature", ISA, Pittsburgh, 1972). The doped germanium resistance thermometer is widely used to preserve the cryogenic temperature scale in the same way that platinum resistance is used at higher temperatures. The reproducibility of selected germanium thermometers is better than 1 millikelvin from 4 K down to .02 K, and the devices are useful to temperatures as high as 20 K. Basically semiconductors, these resistors show a modified exponential temperature dependence of resistivity, so that the useful span of temperature is about a factor ten or twenty for a given unit. In general they show pronounced magnetic field dependences (L. J. Neuringer, A. J. Perlman, L. G. Rubin, Y. Shapira, RSI, 42, 9 (1971)).
2. Carbon radio resistors. (References: J. R. Clement, E. H. Quinnell, RSI 23, 213 (1952); W. C. Black, Jr., W. R. Roach, J. C. Wheatley, RSI, 35, 587 (1964); A. C. Anderson, p. 773, Part 2, Vol. 4, "Temperature", ISA, Pittsburgh, 1972. H. Weinstock, J. Paupia, p. 785, Ibid.) The carbon radio resistor is a semiconductor whose resistivity, like that of doped germanium, obeys a modified exponential dependence. Its reproducibility is inferior to that of the germanium, but its trivial cost allows its use in low-precision monitoring and control applications below 100 K. Like germanium thermometers, carbon thermometers are quite magnetroresistive.
3. Metals with small amounts of magnetic impurities. (Reference: A. R. Harvey, S. Legvold, and D. T. Peterson, Phys. Rev. B4 4003 (1971)). A small temperature dependent resistivity which occurs in Kondo alloys continues to vary at temperatures of 1 K and below, raising the possibility of secondary thermometry by this means.
4. Metal films. (Reference: A. J. Laderman, G. J. Hecth, and A, K. Oppenheim, Vol. 3,

Part 2, p. 943 of "Temperature", Reinhold, 1962.) Metal film thermometry can be used at temperatures from cryogenic to the melting point of the metal. The sensor is quite fast-responding, but generally not stable in resistance.

5. Thermistors. (References: Sections 29 and 30 by C. R. Droms and H. B. Sachse in Vol. 3, Part 2, p. 339 and p. 347 of "Temperature", Reinhold, 1962.) Basically semiconductors, these sensitive sensors have come into extremely wide use at temperatures up to 300 or 400 °C because of their small size and high sensitivity. They will be further discussed in Section 3.
6. Miniature platinum thermometers. (Reference: D. A. Lucas, Vol. 4, Part 2, p. 963 of "Temperature", ISA, 1972.) These millimeter-size thermometers can display reproducibilities of 10 ppm at the triple point of water, and can be used from 13.8 K to 500 K.
7. Nickel resistance thermometers. (Reference: D. A. Grant and W. F. Hickes, Vol. 3, Part 2, p. 305, "Temperature", Reinhold, 1962.) The use of nickel resistors to meet the ruggedness and interchangeability demands of industry has resulted in their growing use as thermometers.
8. Ceramic thermometers. (References: A. R. Anderson and T. M. Stickney, Vol. 3, Part 2, p. 361, and W. N. Lawless, Vol. 4, Part 2, p. 1143, "Temperature", Reinhold, 1962, and ISA, 1972, respectively). The first reference deals with ceramics as high-temperature resistance thermometers, and the second, with ceramics as cryogenic capacitors, thermometers which are nearly independent of magnetic fields.

APPENDIX F. OTHER TEMPERATURE SENSORS IN MORE OR LESS COMMON USE

1. Paramagnetic susceptibility (χ). Reference: T. C. Cetas and C. A. Swenson, p. 57, Part 1, Vol. 4, "Temperature", ISA, Pittsburgh, 1972.
2. Liquid vapor pressure. Reference: Section I-B, pp. 121-168, Ibid.
3. Noise. Reference: R. A. Kamper, p. 349, Ibid.
4. Acoustic. References: (High temperatures) G. L. Innes, p. 689, Ibid.; (Low temperatures) A. R. Colclough, p. 365, Ibid.
5. Resonant frequency of quartz. Reference: A. Benjaminson, and F. Rowland, p. 701, Ibid.
6. Electronic junction devices. Section IV-F, pp. 1097-1136, Part 2, Ibid.
7. Nuclear resonance. Section V-A, pp. 1197-1238, Ibid.

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The National Temperature Measurement System reaches quite literally into all phases of American life. Comfort control in home, school, office and factory, health care, manufacturing, food preparation and storage, and all forms of powered transportation are just a few of the many facets of America's human activities that depend for their trouble-free operation on the existence of reliable thermometry.

The Heat Division of the National Bureau of Standards collaborates with the national laboratories of other nations in establishing an International Practical Temperature Scale which represents thermodynamic accuracy insofar as current scientific practice permits. The NBS is the only U.S. agency bearing this responsibility; in addition, only the NBS is responsible for disseminating the International Scale to U.S. scientific and technical activities.

The Study of the National Temperature Measurement System shows that the NBS continues to contribute energetically to the quality of the International Scale. It further indicates that NBS maintains a consistent and deliberate effort not only to provide access to the Scale at the several levels required by U.S. science and technology, but also to participate in solving special problems in thermometry. These are problems for which the nature of NBS as an objective, expert resource in thermometry uniquely qualifies it to furnish effective, practical solutions.

In briefly describing the many aspects of the National Temperature Measurement System, this Study attempts to portray its great diversity of products, services, and people. The System is largely organized, as might be expected, for the purpose of economic gain; the NBS enters the picture only in those areas where highly accurate or intricate thermometry is essential.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

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