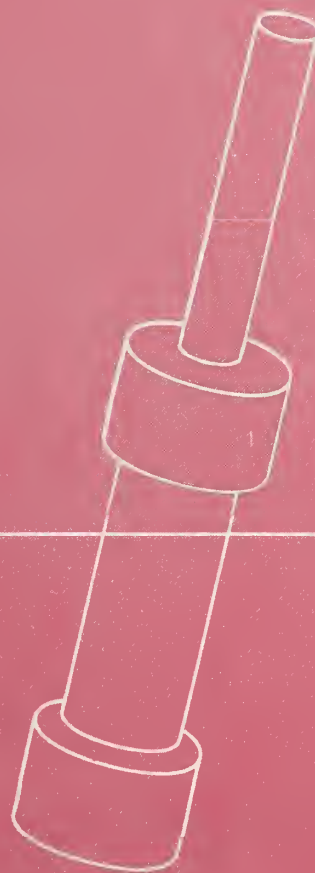# NBS SPECIAL PUBLICATION 481

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

GALLIUM

MELTING-POINT

STANDARD

NATIONAL BUREAU OF STANDARDS

The National Bureau of Standards[1] was established by an act of Congress March 3, 1901. The Bureau's overall goal is to strengthen and advance the Nation's science and technology and facilitate their effective application for public benefit. To this end, the Bureau conducts research and provides: (1) a basis for the Nation's physical measurement system, (2) scientific and technological services for industry and government, (3) a technical basis for equity in trade, and (4) technical services to promote public safety. The Bureau consists of the Institute for Basic Standards, the Institute for Materials Research, the Institute for Applied Technology, the Institute for Computer Sciences and Technology, the Office for Information Programs, and the Office of Experimental Technology Incentives Program.

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Office of Standard Reference Data — Office of Information Activities — Office of Technical Publications — Library — Office of International Standards — Office of International Relations.

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[1] Headquarters and Laboratories at Gaithersburg, Maryland, unless otherwise noted; mailing address Washington, D.C. 20234.

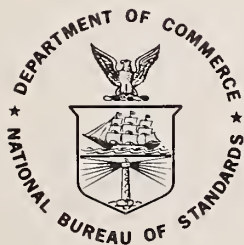[2] Located at Boulder, Colorado 80302.

The Gallium Melting-Point Standard

t. Special Publication no. 481

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Foreword

The investigation of the melting point of gallium as a thermometric reference ("fixed point") and the preparation of a supply of well-characterized, very pure gallium as a NBS Standard Reference material (SRM 1968) have been carried out as part of the Temperature program in the Heat Division. This particular project is designed to address specifically the temperature measurement problems encountered in the medical, clinical, and biomedical areas of U.S. technology. The four articles reproduced from the journal *Clinical Chemistry* and collected here* are being made available to interested parties as a further service to the measurement community within this specialized area, with the hope that they will contribute to improved metrological practice in the identified fields and hence to the quality of the nation's health care.

We are grateful to Dr. J. Stanton King, Executive Editor of *Clinical Chemistry,* for kindly making available negatives of the four articles and thus greatly facilitating the preparation of this Special Publication.

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R. P. Hudson
Chief, Heat Division

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*References within the articles to specific commercial products do not in any way imply endorsement thereof by the National Bureau of Standards.

Contents

Abstract

This Special Publication contains a series of papers published in *Clinical Chemistry* concerning our temperature measurement system, the gallium melting-point as a thermometric fixed-point, how the gallium melting-point fits into the measurement system, and applications of the gallium melting-point standard.

Keywords: Clinical laboratory; fixed-point; gallium; melting-point standard; temperature; thermometric fixed-point.

THE GALLIUM
MELTING-POINT STANDARD

The Gallium Melting-Point Standard: A New Fixed Point to Assure the Accuracy of Temperature Measurements in the Clinical Laboratory

Introduction by George N. Bowers[1]

This series of papers is written to introduce the readers of *Clinical Chemistry* to the use of the melting point of gallium as a means of improving the accuracy of temperature measurements in our nation's clinical laboratories. Gallium, the 32nd most abundant element in the earth's crust, is a silver-grey metal, widely distributed in trace amounts in many rocks and ores. Its name, gallium (Lat., *gallia*, France), honors the discovery of this element by a French chemist in 1875, just four years after Mendeleev predicted its probable existence from a blank space in his newly described periodic table. M. Paul Emile Lecoq de Boisbaudran, although by vocation the owner–operator of a distillery business in Cognac, privately maintained his own spectroscopy laboratory, and in addition to discovering gallium he also discovered scandium in 1879 and germanium in 1886. Today, ultra-high-purity gallium metal is manufactured primarily for the electronics industry to make the semiconductor materials, gallium arsenide and gallium phosphide, used in rectifiers, photocells, transistors, lasers, etc. Interestingly, this metallic element is unique in that it has the widest liquid range of any metal, melting at 29.77 °C and boiling at slightly above 2400 °C. The melting point of highly pure gallium is very sharply defined and is easily maintained constant for many hours. Fortunately, this melting point lies close to the center of the ranges of usual interest in the clinical laboratory.[2] No costly or complex equipment is required to realize 29.77 °C to ±0.01 °C in any clinical laboratory. Thus a small and relatively inexpensive gallium melting-point cell provides an ideal means of calibrating the thermistor probes of electronic thermometers. These small probes with their tiny but stable sensors are essential to accurate temperature measurements in clinical-service and biomedical-research laboratories, because the heat capacity and size of the large mercury-in-glass thermometers would seriously distort temperature within the small volumes of final reaction mixtures commonly used today.

Each of these papers, although contributed by authors of different expertise, backgrounds, and areas of responsibility, supports the concept that temperature measurements for clinical laboratories within the United States (and elsewhere) can be improved considerably by the introduction of the gallium melting-point standard. For this goal to be achieved, a system must evolve within which the following functions and responsibilities are discharged:

(1) *National laboratories* certify and distribute gallium melting-point cells.

(2) *Manufacturers* use these certified gallium melt-ing-point cells (or equivalents) in the production,

[2] The ranges of interest in the clinical laboratory are many and varied; thus, any choice is necessarily arbitrary. We have chosen this to mean either 0–60 °C or 24–38 °C in this series of papers, although 0–105 °C is also given in a recently proposed ASTM Committee E20.08.04 specification for thermistors for use in the clinical laboratory.

quality control, and calibration of the electronic thermometers and related heat equipment manufactured for use in clinical laboratories.

(3) *Clinical laboratory personnel* use these certified gallium melting-point cells regularly to check and to maintain the calibration of these devices.

In the first paper, Mangum, who is a physicist in charge of the Medical Thermometry Project at the National Bureau of Standards (NBS), reviews the primary *defining fixed points* of the International Practical Temperature Scale of 1968 (IPTS-68) and the interpolation role played by platinum resistance thermometry. The Scale is maintained and disseminated by various national standards laboratories throughout the world. In the United States this responsibility resides within the Heat Division of the Institute of Basic Standards of NBS. He tells how the Heat Division disseminates the Scale by calibration services and Standard Reference Materials (SRM's) for use within our industrial, scientific, and medical communities. The historical and current investigational work on gallium is reviewed, and he discusses why gallium is so well qualified as a secondary reference point for the IPTS-68.

In the second paper, Thornton, a professor of physics at The George Washington University, presents his experimental data on small prototype gallium melting-point cells. As trace impurities in the gallium are decreased, the temperature of the melting point is shown to change, becoming progressively higher and more stable. An extremely reproducible melting point at 29.7714 ± 0.0014 °C is demonstrated with cells containing gallium of 99.99999% purity. The design of a similar gallium cell, presently being issued by the NBS Office of Standard Reference Materials as Clinical SRM No. 1968, is given.

In the third paper, Sostman—who is a temperature physicist and vice president for product integrity of Yellow Springs Instrument Co., Inc., manufacturer of electronic thermometers, thermistors, and other temperature-monitoring and controlling equipment—describes how the calibration needs of electronic thermometers are served by the gallium cell. He reviews types of sensors for electronic thermometers and the design considerations of a thermometer system for clinical laboratory practice, and demonstrates that for the range from 29 to 31 °C a single-point calibration to gallium near the center of the range is adequate to ensure calibration within ±0.01 °C. The precautions necessary in making such a calibration by conventional means and the greater ease and certainty of calibration at the gallium point are given. He discusses the development of a gallium cell and the role of the gallium reference point in YSI's metrology standards laboratory.

In the fourth paper, Bowers and Inman—clinical chemist and instrument specialist, respectively—illustrate several uses of a gallium melting-point cell within a hospital clinical chemistry laboratory. The uncertainty of temperature measurements traceable to IPTS-68 on using the gallium melting-point standard is shown to be ±0.01 °C at 29.77 °C, in comparison to prior uncertainty of ±0.03 °C to 0.05 °C at 30 °C and 37 °C for stirred-liquid comparison baths with SRM's 933 and 934 [*cf. Clin. Chem.* **20**, 670 (1974)] as the reference thermometers.

This certainty of calibration at 29.77 °C has been exploited for measurement of the enzymic activity of aspartate aminotransferase in serum by the IFCC reference method. On the basis of this experience, it is suggested that the set-point of the reaction temperature for reference methods in clinical enzymology be made equal to this unique constant-of-nature: the gallium melting-point standard at 29.7714 ± 0.0014 °C.

Many novel applications of this stable temperature reference point can be expected as this unique property of gallium becomes more widely known. However, its most obvious primary and immediate role in the clinical laboratory will be to improve our ability to more accurately measure and control temperature.

The Gallium Melting-Point Standard: Its Role in Our Temperature Measurement System

B. W. Mangum

The latest internationally-adopted temperature scale, the International Practical Temperature Scale of 1968 (amended edition of 1975), is discussed in some detail and a brief description is given of its evolution. The melting point of high-purity gallium (stated to be at least 99.99999% pure) as a secondary temperature reference point is evaluated. I believe that this melting-point temperature of gallium should be adopted by the various medical professional societies and voluntary standards groups as the reaction temperature for enzyme reference methods in clinical enzymology. Gallium melting-point cells are available at the National Bureau of Standards as Standard Reference Material No. 1968.

Although temperature measurements are probably made more often by more people than any other type of measurement, many are not cognizant of *what* temperature scale is being used, the *basis* of that scale, and the *difference* between the thermodynamic and practical temperatures (to say nothing of the relevance of the meter reading). In this article, I shall discuss these points and give a brief history of the evolution of the temperature scale. I shall also discuss the utility of the melting point of gallium as a temperature fixed point, its relationship to the temperature scale, and its great potential in clinical laboratories.

Temperature Scales

The unit of thermodynamic temperature is one of the seven base units of the metric system (*1*). Thermodynamic temperature is referred to as a fundamental physical quantity and is given the symbol T (see Figure 1). This is the relevant quantity in all thermodynamic calculations involving temperature. Its unit is the kelvin (*2*), symbolized K, and this is defined as the fraction 1/273.16 of the thermodynamic temperature of the triple point of water (*3*).

Based on the historical development of temperature scales, temperature is commonly expressed in terms of its difference from that of the thermal state 0.01 K lower than the triple point of water. The temperature expressed in this way is the Celsius thermodynamic temperature, symbol t, and is defined (*4*) by

$$t = T - 273.15 \text{ K}$$

The degree Celsius, having the symbol °C, is the unit of Celsius temperature and by definition it is equal in magnitude to the kelvin. A difference of temperature may be expressed in either kelvins or degrees Celsius.

Before the turn of the century, it was recognized by the International Committee for Weights and Measures (CIPM) that an international practical temperature scale was needed so that all temperature measurements could be put on the same basis. The purpose would be to overcome the practical difficulties of the direct realization of thermodynamic temperatures by gas thermometry and to unify the existing national temperature scales. This led to the adoption of the International Temperature Scale of 1927 by the 7th General Conference of Weights and Measures (*5*). This internationally-agreed-upon scale was intended to be easily and accurately reproducible and to agree with thermodynamic temperatures.

The International Temperature Scale of 1927 was revised in 1948 (*6*), and an amended edition of it was adopted in 1960 by the 11th General Conference of Weights and Measures (*7*) under the new title "International Practical Temperature Scale of 1948 (amended edition of 1960)." It was recognized at that time that the scale no longer represented the thermodynamic temperatures as closely as possible.

In 1967, the 13th General Conference of Weights and Measures (*8*) gave the CIPM permission to introduce a new temperature scale to replace the existing International Practical Temperature Scale of 1948 as soon as the Advisory Committee on Thermometry (CCT) to

THERMODYNAMIC TEMPERATURE

Fundamental Laws defining Thermodynamic Temperature

$$\frac{T - 273.16}{T} = \frac{W}{Q} \quad \text{(Carnot's Law)}$$

$$\frac{T}{273.16} = \frac{\lim\limits_{P \to 0} PV}{\lim\limits_{P \to 0} P_oV_o} \quad \text{(Gas Law)}$$

$$L_\lambda = \frac{C_1}{\lambda^5 \left[\exp\left(\frac{C_2}{\lambda T}\right) - 1\right]} \quad \text{(Planck's Law)}$$

T = Thermodynamic Temperature
W = Work Performed in Carnot Cycle
Q = Heat Exchanged at Higher Temperature in Carnot Cycle

P_o = Pressure at 273.16K
V_o = Volume at 273.16K

L_λ = Spectral Concentration of Black Body Radiance
λ = Wavelength
C_1, C_2 = Constants

INTERNATIONAL PRACTICAL TEMPERATURE SCALE OF 1968 (AMENDED EDITION OF 1975)

The IPTS-68 (amended edition of 1975) is based on the assigned values of the temperatures of 13 defining Fixed Points and on Standard Instruments calibrated at those temperatures. Specified Interpolation Functions for the Standard Instruments provide a means of calculating intermediate temperatures.

POINTS FIXED / STANDARD INSTRUMENTS

OPTICAL PYROMETER

1064.43 °C / 1337.58 K	F.P. of Au
1235.08 K / 961.93 °C	F.P. of Ag
630.755 °C	F.P. of Sb (a secondary point)

Pt+10%Rh vs. Pt Thermocouple

419.58 °C / 692.73 K	F.P. of Zn
231.9681 °C / 505.1181 K	F.P. of Sn
100 °C / 373.15 K	B.P. of H_2O
0.01 °C / 273.16 K	T.P. of H_2O

Platinum Resistance Thermometer

90.188 K	Cond. point of O_2
83.798 K	T.P. of Ar
54.361 K	T.P. of O_2
27.102 K	B.P. of Ne
20.28 K at 25/76 Std. Atm.	B.P. of equil. H_2
17.042 K	B.P. of equil. H_2
13.81 K	T.P. of equil. H_2

SECONDARY REFERENCE POINTS

1963 °C	F.P. of Rh
1769 °C	F.P. of Pt
1455 °C	F.P. of Ni
1084.88 °C	F.P. of Cu
660.46 °C	F.P. of Al
548.26 °C	M.P. of CuAl eutectic
444.674 °C	B.P. of S
356.66 °C	B.P. of Hg
271.442 °C	F.P. of Bi
156.634 °C	F.P. of In
122.37 °C	T.P. of benzoic acid
26.87 °C	T.P. of phenoxybenzene
0 °C	Ice point
-38.836 °C	F.P. of Hg
-78.476 °C	Sub. Point of CO_2
-185.856 °C	B.P. of Ar
-195.806 °C	B.P. of N_2
-210.004 °C	T.P. of N_2
-248.589 °C	T.P. of Ne
-252.753 °C	B.P. of Normal H_2
-259.194 °C	T.P. of Normal H_2

T.P. = Triple Point
B.P. = Boiling Point
Cond. Point = Condensation Point
F.P. = Freezing Point
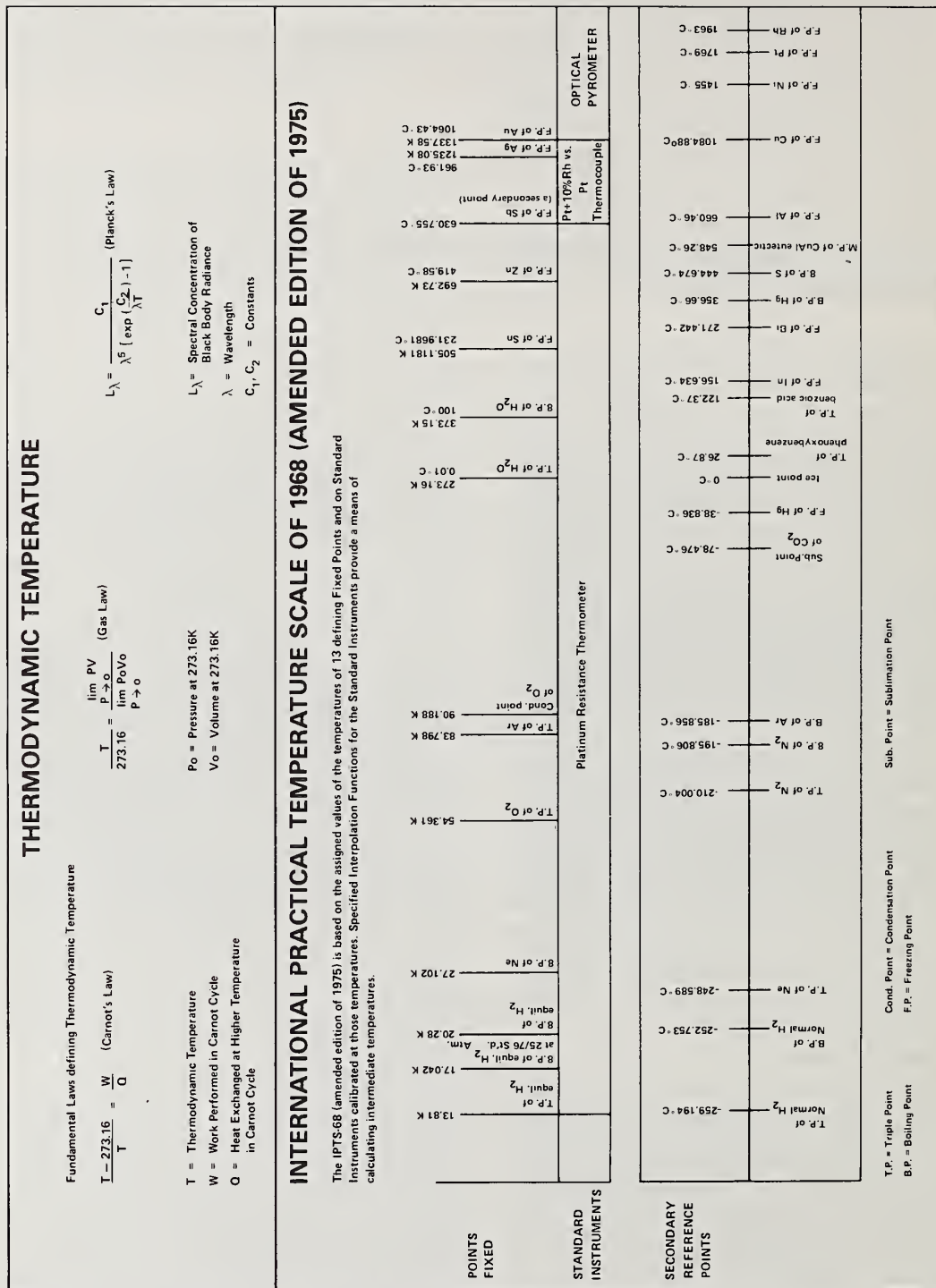Sub. Point = Sublimation Point

Fig. 1. Guide to thermodynamic temperatures and to the International Practical Temperature Scale of 1968 (amended edition of 1975)

Not all of the secondary reference points are shown

Table 1. Defining Fixed Points of the IPTS-68 [a]

Fixed points	Assigned value of International Practical Temperature	
	T_{68}(K)	t_{68}(°C)
Triple point of equilibrium hydrogen [b]	13.81	−259.34
Boiling point of equilibrium hydrogen at a pressure of 33 330.6 Pa (25/76 standard atmosphere) [b,c]	17.042	−256.108
Boiling point of equilibrium hydrogen [b,c]	20.28	−252.87
Boiling point of neon [c]	27.102	−246.048
Triple point of oxygen	54.361	−218.789
Triple point of argon [d]	83.798	−189.352
Condensation point of oxygen [c,d]	90.188	−182.962
Triple point of water	273.16	0.01
Boiling point of water [e]	373.15	100
Freezing point of tin [e]	505.1181	231.9681
Freezing point of zinc	692.73	419.58
Freezing point of silver	1235.08	961.93
Freezing point of gold	1337.58	1064.43

[a] Except for the triple points and the equilibrium hydrogen point at 17.042 K, the assigned values of temperature are for equilibrium states at a pressure of 101 325 Pa (1 standard atmosphere). If differing isotopic abundances could significantly affect the fixed point temperatures, the abundances are specified.

[b] Equilibrium hydrogen means that the hydrogen has its equilibrium ortho-para composition at the relevant temperature. "Ortho" and "para" are the designations for the molecular configurations (nuclear spin arrangements) of hydrogen.

[c] Fractionation of isotopes or impurities dictate the use of boiling points (vanishingly small vapor fractions) for hydrogen and neon and condensation point (vanishingly small liquid fraction) for oxygen.

[d] The triple point of argon may be used as an alternative to the condensation point of oxygen.

[e] The freezing point of tin may be used as an alternative to the boiling point of water.

the CIPM could make its recommendations for the new scale. Following the recommendation of the CCT, the CIPM then agreed in 1968 (4) to adopt the new International Practical Temperature Scale of 1968 (IPTS-68). The IPTS-68 extended the scale to lower temperatures to unify the existing national scales in the region 10 K to 90 K and brought the values measured on the scale into agreement with thermodynamic temperatures within the limits of the accuracy of measurement at that time.

The IPTS-68 distinguishes between the International Practical Kelvin Temperature, symbol T_{68}, and the International Practical Celsius Temperature, symbol t_{68},

$$t_{68} = T_{68} - 273.15 \text{ K}$$

The units of t_{68} and T_{68} are the same as for t and T, respectively.

In 1974, the CIPM proposed an amended version of the IPTS-68, and it was adopted by the 15th General Conference of Weights and Measures in 1975 (9). This is only an amended version of the IPTS-68, not a replacement. It differs from the 1968 version in that the argon triple point was introduced as an alternative to the oxygen boiling point; the reference function for the standard platinum thermometer is given in an improved form; the criteria for the selection of thermocouples were changed; the values of some of the secondary reference points have been changed; Table 7 of the original version of IPTS-68, which gave the estimated uncertainty of the assigned values of the defining fixed points, has been deleted; and some inconsistencies and defi-

ciencies have been removed from and additional information added to the section on supplementary information. Any measured temperature, T_{68}, is unchanged by this amended edition.

Work is currently in progress toward extension of the IPTS-68 (amended edition of 1975) to lower temperatures and toward its possible revision.

Defining Fixed Points of the IPTS-68 (Amended Edition of 1975)

The IPTS-68 (amended edition of 1975) is based on the assigned values of the temperatures of 13 reproducible equilibrium states (defining fixed points) and on standard instruments calibrated at those temperatures (see Figure 1). These equilibrium states and the International Practical Temperatures assigned to them are given in Table 1. Between these fixed-point temperatures, there are specified interpolation equations that relate indications of the standard instruments to International Practical Temperatures.

Standard Interpolation Instruments

The platinum resistance thermometer is the standard instrument for the range 13.81 K (−259.34 °C) to 903.89 K (630.74 °C). Strain-free, annealed, pure platinum whose resistance ratio is $R(373.15 \text{ K})/R(273.15 \text{ K}) \geq 1.39250$, where $R(T_{68})$ is the resistance at temperature T_{68}, must be used as the resistor material. A reference function and specified deviation equations provide the resistance–temperature relation below 0 °C, whereas two polynomial equations provide the resistance–temperature relation for the range 0 °C to 630.74 °C.
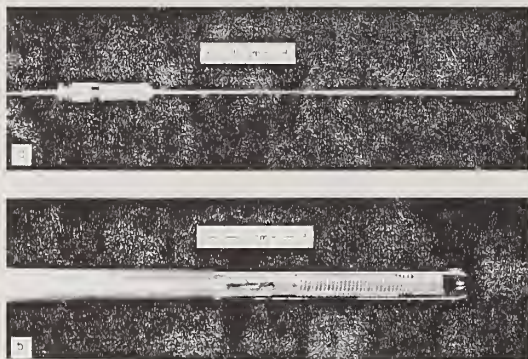
Fig. 2. The Standard Platinum Resistance Thermometer (SPRT)
In *a*, the overall SPRT is shown; in *b*, only the resistance element of the SPRT is shown
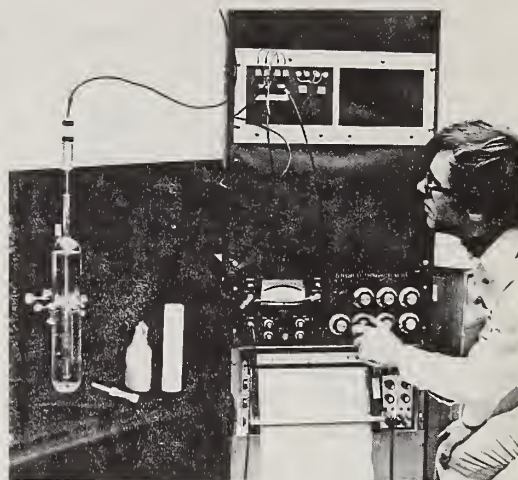

Fig. 3. Calibration of a standard platinum resistance thermometer in a triple-point-of-water cell
The ancillary equipment required for making the measurement is shown. Also shown in this figure are a gallium melting-point cell, a bottle of gallium stated to be 99.99999+% pure, and a prototype of SRM 1968. So that the SPRT and the triple-point-of-water cell could be displayed, the experimental arrangement shown here is not that used in actual measurements. In actual triple-point determinations, the triple-point cell is immersed in an ice bath and a black cloth covers the SPRT and the cell

The platinum-10% rhodium/platinum thermocouple is the standard instrument for the range 903.89 K (630.74 °C) to 1337.58 K (1064.43 °C). Its electromotive force vs. temperature relation is given by a quadratic equation. The purity of the platinum wire of the standard thermocouple must be such that $R(373.15 \text{ K})/R(273.15 \text{ K}) \geq 1.3920$.

Above 1337.58 K (1064.43 °C), the IPTS-68 is defined in terms of the Planck radiation law, with 1337.58 K (1064.43 °C) as the reference temperature and with a specified value for the second radiation constant, c_2, of Planck's law.

For the benefit of those not familiar with the Standard Platinum Resistance Thermometer (SPRT) and its construction, one is shown in Figure 2. A brief description of it follows. The temperature sensing element is a four-terminal pure platinum wire resistor as described above, which is mounted in a strain-free manner and is hermetically sealed in a tube filled with a dry gas containing enough oxygen to stabilize oxide impurities. In order to avoid contamination of the resistor and to minimize Peltier effects, a short length of the leads connected directly to the resistor should be of platinum. The Standard Platinum Resistance Thermometer is very fragile, and either mechanical or thermal shock will introduce defects. These can be removed by annealing. The thermometer should be annealed at a temperature that is greater than the intended operating temperature and if the thermometer is to be calibrated, it should finally be annealed at a temperature equal to or slightly greater than 450 °C. In using the thermometer, care must be taken to avoid thermal radiation and conduction, and, in addition, Joule heating due to the measuring current should be minimized. The latter can be done by using zero-power resistance or by operating at a measuring current that is the same as that used in the thermometer calibration, usually 1 mA. The reliability of a Standard Platinum Resistance Thermometer can be ascertained by the constancy of its resistance at the triple point of water and by the constancy of its resistance ratio for other fixed points. Figure 3 shows measurements being made with a Standard Platinum Resistance Thermometer in a triple-point-of-water cell. So that the SPRT and the triple point of water cell may be displayed, the experimental arrangement shown here is not that used in actual measurements. In actual triple-point determinations, the triple-point cell is immersed in an ice bath and a black cloth covers the SPRT and the cell. The cloth minimizes radiation getting into the cell.

Secondary Fixed Points

In addition to the defining fixed points of the IPTS-68 (amended edition of 1975) given in Table 1, there are other, so-called secondary, reference points available (9). I list some of these in Table 2, and they are shown in Figure 1.

Dissemination of the Temperature Scale

The IPTS-68 is maintained and disseminated by the various national standards laboratories and in this country the responsible institution is the National Bureau of Standards. The dissemination of the Scale is accomplished through calibrations. Those national standards laboratories that perform such calibrations are listed in Table 3. The National Bureau of Standards calibrates thermometers either by making measurements at some or all of the defining fixed points, depending on the temperature range of interest, or by comparison with a Standard Platinum Resistance Thermometer. This ensures that the basis for temperature measurement, the IPTS-68, is the same everywhere throughout the country. Those involved in tem-

Table 2. Secondary Reference Points

Equilibrium state	International Practical Temperature	
	T_{68}(K)	t_{68}(°C)
Triple point of normal hydrogen[a]	13.956	−259.194
Boiling point of normal hydrogen[a]	20.397	−252.753
Triple point of neon	24.561	−248.589
Triple point of nitrogen	63.146	−210.004
Boiling point of nitrogen	77.344	−195.806
Boiling point of argon	87.294	−185.856
Sublimation point of carbon dioxide	194.674	−78.476
Freezing point of mercury	234.314	−38.836
Ice point[b]	273.15	0
Triple point of phenoxybenzene (diphenyl ether)	300.02	26.87
Triple point of benzoic acid	395.52	122.37
Freezing point of indium	429.784	156.634
Freezing point of bismuth	544.592	271.442
Freezing point of cadmium	594.258	321.108
Freezing point of lead	600.652	327.502
Boiling point of mercury	629.81	356.66
Boiling point of sulfur	717.824	444.674
Melting point of the copper-aluminum eutectic	821.41	548.26
Freezing point of antimony	903.905	630.755
Freezing point of aluminum	933.61	660.46
Freezing point of copper	1358.03	1084.88
Freezing point of nickel	1728	1455
Freezing point of cobalt	1768	1495
Freezing point of palladium	1827	1554
Freezing point of platinum	2042	1769
Freezing point of rhodium	2236	1963
Melting point of aluminum oxide	2327	2054
Freezing point of iridium	2720	2447
Melting point of niobium	2750	2477
Melting point of molybdenum	2896	2623
Melting point of tungsten	3695	3422

[a] Normal hydrogen is a mixture of 75% orthohydrogen and 25% parahydrogen.
[b] The ice point is a very close approximation to the temperature defined as being 0.01 K below the triple point of water.

perature measurements and those involved in developing voluntary temperature standards should be aware of the Scale on which their measurements are based.

Clinical Laboratory Needs and the National Bureau of Standards' Response

Discussions with professional organizations and standards-setting groups involved with clinical laboratories have indicated (10–14) that there are some critical temperature measurement and control problems in the clinical laboratory, especially in the area of clinical enzymology. It is difficult for the user to measure the temperature of a reaction mixture accurately or to verify that the temperature control of such a mixture in, say, a cuvette is that which is required. There are many different types of thermometers available for use in the biomedical temperature range, and they provide a wide choice of stability, sensitivity, and ease of use, but their accuracy depends upon their calibration. At the level of accuracy required of temperature measurements in clinical enzymology (15), it is necessary periodically to

recalibrate the thermometer, or to check its calibration, against the International Practical Temperature Scale of 1968. Recalibration is particularly important for many of the new electronic thermometers that depend on sensitive resistive elements, thermistors, as sensors. The low cost, convenience, and high sensitivity of these thermometers make them attractive, but their complex temperature characteristics—as well as the possibility of significant calibration drift—make it highly desirable to have readily available a means of calibrating them.

The College of American Pathologists has indicated (16) that there is a need in the laboratories for temperature fixed points in the temperature range of biological interest. To be useful to the biomedical community, these temperature reference points should be well-defined to ±0.002 °C and both stable and reproducible to ±0.005 °C. Such a set of accurately known temperature-reference points, conveniently spaced throughout the interval from −20 °C to 120 °C, is required if calibration of thermometers is to be accurate. As can be seen in Tables 1 and 2, there is only one such

Table 3. National Standards Laboratories That Calibrate Thermometers

Country	National Standards Laboratory
Australia	National Measurement Laboratory (NML)
Canada	National Research Council (NRC)
Federal Republic of Germany	Physikalisch Technische Bundesanstalt (PTB)
France	Institute National de Metrologie (INM)
German Democratic Republic	Deutsches Amt fur Mass und Gewicht (DAMG)
Italy	Istituto di Metrologia "G. Colonnetti" (IMGC)
Japan	Ministry of International Trade and Industry's National Research Laboratory of Metrology (NRLM)
Russia	Physico-Technical and Radio-Technical Measurement Institute (PRMI) Mendeleev Institute (VNIIM)
United Kingdom	National Physical Laboratory (NPL)
United States	National Bureau of Standards (NBS)

fixed point between the triple point and the boiling point of water. That solitary point is the secondary reference point provided by the triple point of phenoxybenzene (diphenyl ether) at 26.87 ± 0.01 °C. There are problems associated with realizing this point because the material is an organic compound and, as is the case for most organic materials, it is difficult to purify and has a very small thermal conductivity. The result is that the triple point of phenoxybenzene is not a very convenient reference point. Thus, there are no useful fixed points in this temperature region of crucial importance to clinical laboratory scientists and physicians.

In response to these clinical laboratory thermometry needs, the National Bureau of Standards established the Medical Thermometry Project. It is working to alleviate the paucity of fixed points in the range of biomedical interest by adequately documenting a series of such points throughout the range. These fixed points will be characterized regarding melting behavior, sample size, sample design, and handling.

Gallium Melting Point as a Temperature Fixed Point

Appropriateness

Of several possible choices for secondary reference points in the biomedical temperature range, the most obvious one is that of the melting point of gallium. This is because it is near 30 °C, in the range of crucial importance to the medical community, and because gallium can be obtained in highly pure form. The melting point rather than the freezing point is suggested as the appropriate equilibrium state because there are some minor problems associated with ascertaining the

freezing point. The problem is not the overall super-cooling of the gallium, which can be circumvented, but it may be related to local supercooling throughout the sample due to poor thermal conductivity (17, 18) and to pressure effects (19). I refer the reader to the second paper of this series for more details on this.

Recently, it has been proposed that the melting point of gallium is suitable for and should be used as a clinical fixed point (20). In fact, it is highly suitable to serve as a superior secondary fixed point of the International Practical Temperature Scale, and it has been proposed for that also (21). There are several obvious reasons for adopting the melting point of gallium as a secondary reference point. Some of these are: gallium can be obtained in highly pure form (stated to be at least 99.99999% pure) and it is commercially available at that high purity; it is inexpensive; no complicated and expensive equipment is required to obtain or realize the melting point, and the melting-point temperature can be easily realized even by untrained personnel; the melting-point temperature is very sharply defined, the constancy of the melt temperature (±0.0001 m °C or better) is impressive, and a melt can be maintained for a fairly long time (hours) even with a small sample of gallium and with a relatively large temperature gradient between it and its surroundings (see Figure 5 of the following paper). With advantages such as these, it seems likely that the melting point of gallium will be adopted by the CIPM as a secondary reference point and, furthermore, in the future (at, say, the next planned revision of the Scale in the mid-nineteen-eighties) it could become a primary or defining fixed point for the International Practical Temperature Scale.

Gallium melting and freezing points have been investigated for many years, and Table 4 lists the temperature values reported by the researchers for those points (19, 20, 22–27). It has only been within the last decade, however, that the metal has become commercially available in high-purity form. Ths is due primarily to the need for such highly pure gallium by the semiconductor industry. Although 99.99999% pure gallium has been commercially available for only a few years, Roeser and Hoffman (23) of the National Bureau of Standards apparently had good success in purifying their samples, because the temperature of the solid–liquid equilibrium point that they reported in 1934 is in good agreement with the values obtained by recent workers (20, 25–27) (see Table 4).

Because the melting-point temperature of gallium (29.771_4 °C) is in the region of crucial importance to clinical laboratories, and because gallium has the advantages listed above, it should be of tremendous utility to the biomedical community as a temperature reference point. Toward this end, about 25 g of high-purity gallium under argon gas in a melting-point cell is available as a temperature reference point standard, Standard Reference Material (SRM) No. 1968, from the Office of Standard Reference Materials of the National Bureau of Standards (NBS).

Table 4. Published Temperatures of the Equilibrium State between the Solid and Liquid Phases of Gallium [a]

Equilibrium state	Ref. [a]	Reported temperature (°C)	International Practical Temperature	
			$T_{68}(K)$	$t_{68}(°C)$
Melting point	19	29.752	302.893	29.743
Freezing point	22	29.755	302.896	29.746
Freezing point	23	29.780 ± 0.005	302.921 ± 0.005	29.771 ± 0.005
Melting point	24	29.75	302.90	29.75
Melting point	20	29.772 ± 0.002	302.922 ± 0.002	29.772 ± 0.002
Freezing point	25	$29.769_7 \pm 0.0006$	$302.919_7 \pm 0.0006$	$29.769_7 \pm 0.0006$
Melting point	26	29.770 ± 0.002	302.920 ± 0.002	29.770 ± 0.002
Melting point	27	$29.771_4 \pm 0.001_4$	$302.921_4 \pm 0.001_4$	$29.771_4 \pm 0.001_4$
Melting point [b]		$29.772_1 \pm 0.0002_5$	$302.922_1 \pm 0.002_5$	$29.772_1 \pm 0.0002_5$

[a] The values of temperature are for equilibrium states at a pressure of 101 325 Pa (1 standard atmosphere).
[b] Thornton, D. D., and Mangum, B. W., to be published.

Potential Applications of the Gallium Melting-Point Temperature as a Temperature Fixed Point

The International Federation of Clinical Chemists, the American Association for Clinical Chemistry, and the National Committee for Clinical Laboratory Standards have been trying to reach a consensus on a unique reaction temperature for enzyme reference methods. The temperatures under consideration are 25, 30, and 37 °C. Until now, the choice has been arbitrary, with no agreement about the scientific evidence to justify selecting one instead of the others.[1] As a result of the work of the NBS on the melting point of gallium and its proposed adoption as a secondary reference point, however, it seems to me that the arbitrariness of the choice of the temperature for the enzyme reference methods has now been removed. I suggest that the temperature of the melting point of gallium ($29.771_4 \pm 0.001_4$ °C) be selected as *the* reaction temperature for reference methods in clinical enzymology. Because SRM 1968 is now available, there is a real possibility of *every* clinical laboratory having direct access to this reference temperature on the IPTS-68 for enzyme reactions conducted in those laboratories.

The use of the melting-point temperature of gallium as a temperature fixed point in the calibration of thermometers, performed by untrained personnel *in the laboratory in which the thermometers are to be used*, is another potential application of great import. A series of temperature fixed points comprising the ice or triple point of water, the melting point of gallium, and others being developed throughout the range of biomedical interest, will permit each and every laboratory to have its own temperature standards laboratory. One will then have the capability of performing accurate thermometer calibrations directly and easily vs. the IPTS-68. At the present time, the accuracy of a thermometer's calibration can be easily ascertained at two temperatures by means of the gallium fixed-point standard and the ice

point, but this is not sufficient to permit a calibration to be made.

In summary, this brief review of our temperature-measurement system should lead to a better understanding of the temperature scales, how they have evolved, and how they are maintained and disseminated by the National Bureau of Standards. The excellence of the melting point of gallium as a secondary temperature fixed point has been abundantly demonstrated. It is suggested that the temperature of the melting point of pure gallium be adopted in clinical enzymology as *the* reaction temperature for enzyme reference methods. We hope that this suggestion will be approved by the various professional societies and the voluntary standards groups.

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The Gallium Melting-Point Standard: A Determination of the Liquid–Solid Equilibrium Temperature of Pure Gallium on the International Practical Temperature Scale of 1968

Donald D. Thornton

The sharpness and reproducibility of the gallium melting point were studied, and the melting temperature of gallium in terms of IPTS-68 was determined. Small melting-point cells designed for use with thermistors are described. Nine gallium cells including three levels of purity were used in 68 separate determinations of the melting point. The melting point of 99.99999% pure gallium in terms of IPTS-68 is found to be $29.771_4 \pm 0.001_4$ °C; the melting range is less than 0.0005 °C and is reproducible to ±0.0004 °C.

Other papers in this series discuss the need for accurate thermometry in the clinical laboratory and the role of temperature reference points in establishing a useful temperature scale of the required accuracy. Although the gallium point is, in itself, not a complete solution to the problem of accurate thermometry in the clinical laboratory, it represents significant improvement by providing a reference point at a particularly important temperature.

The purpose of this paper is to document the gallium melting point for use as a reference point. Consequently, this paper will discuss briefly the general characteristics of melting and freezing points, describe the pertinent properties of gallium, detail the considerations in the design and construction of melting-point cells, describe briefly the procedures followed in this characterization of the melting point, and present the results of a large number of melting-point determinations.

Melting Points and Freezing Points

The transition of a pure metallic element from the solid phase to the liquid phase at constant pressure is a "first-order" transition, which involves a latent heat of fusion at a fixed temperature. Thus, if heat were applied at a fixed rate to a quantity of a pure metallic element, the temperature of the sample would rise until

the solid–liquid transition was encountered. During the melting process, the temperature would remain constant, rising again only after the material was completely melted. Upon removing heat from the liquid at a constant rate, the reverse would occur; the temperature would fall until the solid began to form, remain constant during freezing, and fall again only after all the material had solidified. This highly idealized situation is indicated graphically in Figure 1a.

Four properties of real materials change this description somewhat, even for very nearly pure samples. First of all, melting or freezing generally occurs at a surface, the interface between the liquid and the solid phases. Because a solid always has a surface at which melting may occur, the previous description of melting is unaltered. A liquid, however, has no preferred locus at which freezing may start. A small quantity of liquid must "nucleate," i.e., form a microcrystallite. For nucleation to occur, the temperature of at least some of the liquid must be lowered *below* the liquid–solid transition temperature. Thus, in freezing we observe supercooling of the liquid below the transition temperature until nucleation occurs. A period of recalescence follows, during which the latent heat released by the initial freezing of the microcrystallites warms the rest of the material back to the liquid–solid equilibrium temperature.

The second complicating property of real materials is the finite thermal conductivity of the material; for heat to pass from one point in the sample to another, there must be a temperature difference between the two points. This temperature difference is sometimes referred to as a "driving gradient," or just "gradient." In melting or freezing, such a gradient is needed between the bath and the liquid–solid interface to remove or supply the latent heat. The size of this gradient determines the rate at which melting or freezing may occur. The combined effects of supercooling and thermal conductivity are illustrated in Figure 1b, where the temperature plotted corresponds to that indicated by
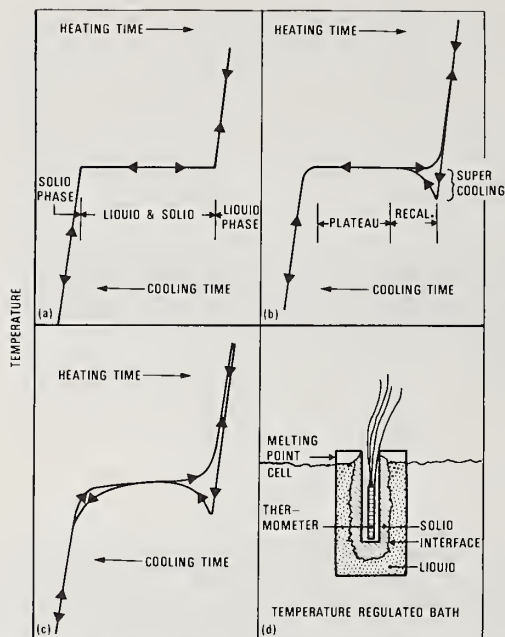
Fig. 1. Schematic melting and freezing curves showing the temperature indicated by a thermometer in the re-entrant well as shown in (d)

(a) No impurities, no supercooling and no resistance to heat flow; (b) supercooling and finite thermal conductivity, but no impurities; (c) supercooling, finite thermal conductivity, and a low content of impurities

a thermometer in a central well surrounded by solid during melting or freezing (Figure 1d).

A third material property affecting the melting or freezing of pure elements is the dependence of the liquid–solid equilibrium temperature on pressure. The pressure on the material must be kept constant in order for the liquid–solid transition to occur at a single, well-defined temperature. If the pressure were allowed to vary freely, the transition would be "broadened," i.e., occur over a range of temperatures rather than at a single temperature.

Finally, it is nearly impossible to completely remove all impurities from any material. Only impurities that are soluble in the liquid or the solid, or both, will affect the melting or freezing behavior significantly. A very minute quantity of an impurity may simply raise or lower the phase equilibrium temperature, but any significant quantity will broaden the transition as shown in Figure 1c.

In light of the above discussion, some of the reasons why the liquid–solid phase transitions of pure metals generally make such excellent temperature reference points are: the latent heat of fusion naturally maintains the sample at the transition temperature for some time; the high thermal conductivity of most metals assures that temperature gradients in the metal will be small; the metals can usually be highly refined; the degree of supercooling is normally quite small; and the pressure

dependence of the transition temperature is usually small enough to ignore.

Properties of Gallium

Although gallium is not a common element, it has become available commercially in very pure form as a result of its importance to the semiconductor industry. The highest purity material that is readily available from commercial sources is 99.99999% (7N's),[1] in quantities ranging from a few grams to several kilograms.

Gallium is a group III B metal, with atomic weight 69.72. Chemically it is similar to aluminum except that it is not as reactive with the common acids and bases; and it oxidizes only slowly in dry air, though the presence of moisture accelerates the process (1). Because many metals such as zinc, aluminum, and copper are very soluble in gallium, it is important in maintaining purity to avoid contact with metal and metal-containing materials.

Gallium does not have the lowest melting point of the metallic elements, but it does have the largest liquid range, from 29.77 °C to about 2400 °C. Over much of this range, the vapor pressure is very low, less than 10^{-2} Pa ($\sim 10^{-4}$ mmHg) below 900 °C. At normal pressures, gallium crystallizes in the pseudotetragonal form at 29.77 °C, with a density of 5.904 g/cm³, releasing a latent heat of fusion of 80.3 J/g. The density of the liquid is 6.095 g/cm³, so there is a 3.2% expansion on freezing. This, combined with an ability to easily wet glass, makes it inadvisable to store gallium in glass containers. The melting point of gallium is quite pressure dependent, decreasing 0.02 °C/MPa (1 MPa $\simeq$ 10 std. atmospheres) (2). The heat capacities of liquid and solid gallium are approximately 0.375 J/g °C near the melting point; the thermal conductivities are about 29 W/m °C. The thermal conductivity quoted is for polycrystalline samples, because single crystals of gallium exhibit large anisotropy in thermal conductivity, as well as in electrical resistivity, thermal expansion, and the elastic constants (3).

Melting-Point Cells

In general practice, the melting- or freezing-point cells used for calibrating thermometers involve large samples with masses between 0.5 and 1 kg. Clearly, a 500-g sample of gallium would be very expensive, so we were interested in determining the smallest quantity that would provide a sharp, stable point during several hours. Because the need for recalibration is more pressing for thermistors than for liquid-in-glass thermometers, we started with a thermometer well that was designed to accept most electronic thermometer probes. The material chosen for the thermometer well was nylon, the idea being that the roughened surface of machined nylon might facilitate nucleation of the gallium. Thus, the metal would freeze from the well out-

[1] A purity of (e.g.) 99.99999% is often referred to as "7N's" purity, of 99.999% as "5N's" purity, etc.

ward, once a layer of solid had formed. To what extent nylon is better than other materials we do not know, but we have had good success in freezing the metal to it. Other materials—including glass, polyethylene, and Teflon—were used for the outer portions of trial cells of different shapes and sizes. The thermal properties of the glass cells were good, but extreme care had to be taken to avoid breakage. Although most plastics are sufficiently soft or flexible that breakage would not be a problem, they conduct heat very poorly. Consequently, it was desirable to make the cell walls as thin as possible. Because polyethylene is slightly permeable to water vapor (and presumably to air) the chance of contamination with gallium oxide is probably high for cells of this material. Polycarbonate cells can be made with thin but vacuum-tight walls, which are also strong enough to confine the expansion of the gallium without breaking. If the 3.2% expansion were completely confined, the freezing point would be broadened by the resulting pressure over as much as 2 °C. Teflon is soft enough to obviate this problem and is also vacuum tight. Figure 2 shows a typical gallium melting cell, available as Standard Reference Material No. 1968. The polyethylene cells used for most of the determinations differ from the Teflon cells shown only in that the outer wall was made from polyethylene. Preliminary results indicated that in cells with less than 15 g of gallium, and with annular spaces of less than 2 mm, or in which the re-entrant well penetrated to within 2 mm of the bottom of the cell, the indicated melting temperature was very sensitive to the bath temperature. On the other hand, samples of 20 g produced stable indicated melting temperatures that were nearly independent of bath temperature for 2 to 10 h, the duration depending on the bath temperature.

Samples

Because the main emphasis of this study was simply to determine the suitability of the gallium liquid–solid phase transition as a temperature reference point in clinical laboratories, I made no attempt to survey a large number of suppliers or to obtain the highest purity material available. Consequently, there is no systematic study of the effects of various specific impurities or possible variations in the isotopic content on the transition temperature. It was important to verify that material of different purity from different sources reproduced the melting temperature with suitable precision, i.e., to within 0.005 °C. To this end, five samples representing three grades of purity were obtained from two different sources. Two samples of 7N's pure gallium came from a single lot; two samples of 5N's pure gallium came from two different lots; and one sample of 3N's pure gallium was also obtained.

All samples were received in polyethylene containers that had been sealed under argon. The gallium was transferred to the melting-point cells in a dry argon atmosphere so that the cells were sealed in a dry, inert atmosphere. The cells used in the final melting-point determinations are indicated in Table 1.
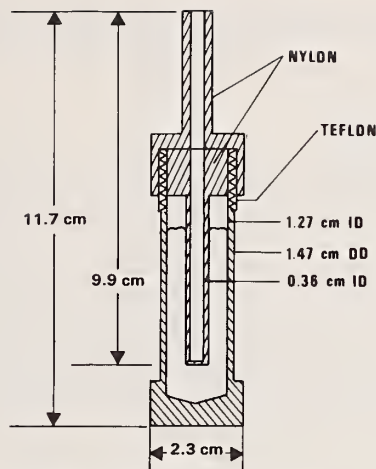

Fig. 2. A cross-sectional drawing of a SRM No. 1968 gallium melting-point cell

The cells used in this study were the same except that the outer walls were of polyethylene and the base was nylon. Such a cell would contain from 20 to 25 g of gallium

The purities listed are those given by the supplier. No analyses for the particular lot were supplied with these samples, although a "typical" spectroscopic analysis from the supplier of the 7N's material indicated 0.05 ppm (0.05 μg/g) of copper as the only impurity detected. At the end of this study, samples from cells G79O2, G59O2, and G59A4 were submitted to the Analytical Chemistry Division of the National Bureau of Standards (NBS) for spectrochemical analysis. The report of analysis listed no detectable impurities in the 7N's material, indicating an upper limit of a few tenths of a microgram per gram for the common metals. In the 5N's gallium from Lot No. 3792, 0.1 μg of silver and 0.5 μg of copper per gram (ppm) were reported. The only impurity detected in the 5N's gallium from Lot No. 1226 was 1 μg of copper per gram. The report stated that the impurity figures were only approximate and that the actual values could have been either larger or smaller by as much as a factor of two. In either case, it is clear both that the suppliers' grade of purity is substantially correct, and that the handling procedures followed in this study have not significantly affected the purity of the samples.

This latter conclusion is important, given the method of constructing the melting-point cells. All parts were machined with carefully cleaned tools, then cleaned in

Table 1. Melting-Point Cells Used in This Study

Cell No.	Purity	Origin
G79O1, G79O2	99.99999%	Lot 081474 sample 1
G79A1, G79A2	99.99999%	Lot 081474 sample 2
G59A4, G59A5	99.999%	Lot 1226
G59O1, G59O2	99.999%	Lot 3792
G39O1	99.9%	

a detergent solution to remove any grease acquired in handling. After they were rinsed thoroughly in distilled water and dried, the cells were assembled under an argon atmosphere.

Thermometry

The objects of this study were to establish the sharpness and reproducibility of the gallium fixed point and to determine the value of the equilibrium temperature in terms of IPTS-68. Because these cells were designed for use with thermistors, it was not feasible to measure the temperature of the cell directly with a standard platinum resistance thermometer. Thus, the following procedure was followed. The resistances of three thermistors were determined at 10 °C intervals from 0 to 60 °C. An analytic expression[2] relating resistance to temperature was fitted to the data. These thermistors were used in the gallium cells for several series of melting-point determinations. Immediately following each series of determinations, these thermistors were compared with a standard platinum resistance thermometer at several temperatures between 28 and 30 °C in a constant temperature bath of high homogeneity. We estimate that this procedure resulted in an uncertainty of ±0.001 °C in the thermistor determinations of temperatures on the IPTS-68 (see below).

The thermistors were bead-type thermistors, each sealed in a glass envelope of diameter 0.31 mm and nominal 25 °C resistance between 12 and 15 kΩ. The resistance of each thermistor was determined by using a digital voltmeter to measure the voltage across the thermistor and the voltage across a 10-kΩ standard resistor when the thermistor and standard resistor were connected in series with a constant-current source. These measurements were "four-lead" measurements, with the current first in the normal direction and then reversed. The constant-current source supplied a current of 10^{-6} A, which was independent of circuit resistance and stable to one part in 10^5. The digital voltmeter had an input impedance of 10^9 Ω and displayed six digits with a 10^{-7} V sensitivity. Thus, the limiting precision of the measuring equipment corresponded to 0.0002 °C in the determination of the temperature.

The International Practical Temperature Scale was realized by a long-stem Standard Platinum Resistance Thermometer, the resistance of which was compared to that of a thermostated 100-Ω standard resistor, by use of a Cutkosky AC Resistance Bridge (5). For the calibration of the thermistors, both the thermistors and the Standard Platinum Resistance Thermometer were immersed in a stirred constant-temperature bath in which the temperature could be regulated to better than ±0.0005 °C. Each of these calibrations included a determination of the platinum resistance at the triple point of water.

[2] The standard equation is known as a Steinhardt–Hardt fit; see, for example: Steinhardt, J. S., and Hart, S. R., Calibration curves for thermistors. *Deep-Sea Res.* **15**, 497 (1968).
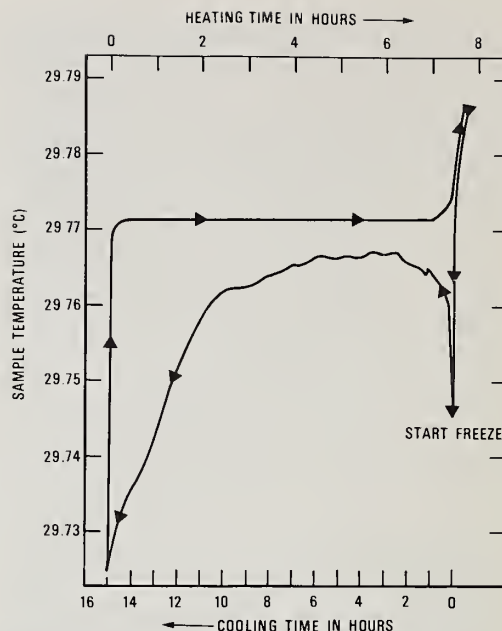
Fig. 3. Combined melting and freezing curves for 99.99999 % pure gallium
Because the gradients were slightly different the time scales for the two curves are different. The supercooling was much deeper than shown, because the freeze was nucleated by a very cold rod, but the initial recalescence was as fast as shown

The major uncertainties in realizing the IPTS-68 temperatures on using the thermistors were: (*a*) calibration of the thermistors, ±0.0005 °C; (*b*) possible drift of thermistors between calibration, ±0.0002 °C; and (*c*) limiting precision of the measurement, ±0.0002 °C. An additional uncertainty arises from the possibility of a difference in thermistor self-heating effects in the calibration bath and the gallium cells; this may be as much as ±0.0002 °C. Thus, as stated above, the overall uncertainty in the temperatures determined by the thermistors is about 0.001 °C.

Results

It is interesting to compare the melting and freezing behavior of gallium with the idealized behavior shown in Figure 1. Figure 3 shows typical melting and freezing curves for 7N's gallium; clearly, the 7N's gallium *melts* in a nearly ideal fashion, but the freezing curve exhibits a deep supercooling, which was terminated by nucleating the freeze with a cold rod inserted into the thermometer well. The recalescence is extended and irregular. The plateau is poorly defined, relatively brief, and well below the melting curve. This freezing behavior results partly from the exaggerated supercooling and the poor thermal conductivity of the metal. The pressure dependence of the equilibrium temperature may also be a factor. If the growth of the solid were sufficiently irregular, regions of freezing liquid could be trapped so that the 3.2% expansion on freezing would
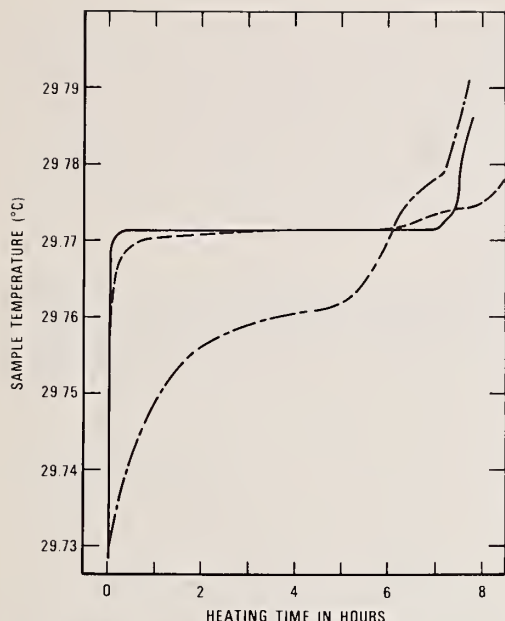
Fig. 4. Melting curves of 99.99999% ("7N's"), 99.999% ("5N's"), and 99.9% ("3N's") pure gallium for about the same gradient in each case is shown by —, - - -, and – · – ., respectively

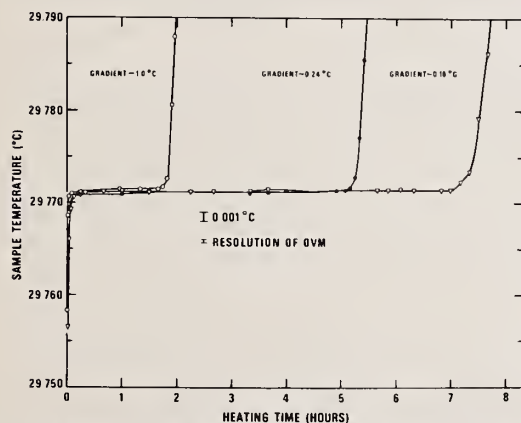The shape of the 3N's curve is very sensitive to magnitude of the gradient

Fig. 5. Melting curves of 99.99999% pure gallium for several different gradients

Table 2. Melting-Point Temperatures of Nine Gallium Cells

Cell	Av melting temp, °C	SD, °C
G79A1	29.7716	±0.0001 (4)
G79A2	29.7716	±0.0003 (6)
G79O1	29.7714	±0.0003 (16)
G79O2	29.7713	±0.0004 (12)
G59O1	29.7712	±0.0002 (6)
G59O2	29.7712	±0.0002 (8)
G59A4	29.7703	±0.0002 (6)
G59A5	29.7701	±0.0005 (5)
G39O1	29.76[a]	

[a] This figure is approximate, because the melting point is not well defined at this purity. See Figure 4. Figures in parentheses are no. detns. averaged.

samples were first preheated in the bath at about 29.70 °C. At time 0, the bath temperature was raised to the value indicated for each curve and regulated at that temperature for the duration of the melting period. These curves exhibit the temperature dependence expected for the melting of relatively pure material. In fact, for all of the curves shown in Figure 5, the temperature variation on the melting plateau is of the same order as the instrument resolution (i.e., ±0.0002 °C). Also, it is important to note that the difference between bath temperature and cell temperature has no effect other than to change the duration of the melt, which shows that the thermometer well is sufficiently deep to ensure that the thermometer is indicating the temperature of the gallium. This was confirmed by withdrawing the thermistor during the melting period. The temperature was found to be constant over about a centimeter, but after further withdrawal the temperature rose rapidly. Clearly, the necessary depth of insertion will be quite sensitive to the details of the thermometer probe, so this is an important consideration in designing a melting-point cell. Both the length of cell and the diameter of the thermometer well may be adapted to various probes, although longer cells will, of course, require more gallium.

In contrast to the melting behavior of the 7N's samples, the 5N's gallium takes somewhat longer to reach a "constant" melting plateau; moreover, during the melting period, the cell temperature shows a constant rise. This behavior is expected, given the higher content of impurities. Nevertheless, if one were working at a precision of ±0.003 °C, it would not be possible to distinguish the melting behavior of the 5N's gallium from that of the 7N's material.

Table 2 shows the results of 65 determinations of the melting points of nine different cells representing three degrees of impurity. Listed are the average melting temperatures and the standard deviations, with the number of determinations that were averaged indicated parenthetically. Each determination represents the value obtained for the melting point with a given thermistor. In some cases up to three thermistors were

result in strains that would broaden the transition as already discussed. In any case, it is clear that obtaining reliable and well-defined freezing curves with small quantities of pure material is at least difficult. Consequently, nearly all of the effort reported here deals with the melting point. Figure 4 illustrates the effects of impurities by showing the melting curves of 7N's, 5N's, and 3N's gallium; Figure 5 illustrates the effects of different bath temperatures during the melting of a sample of 7N's gallium. In the last two figures, the

used in a single "melt," resulting in three determinations of that melting point. Evidently there is no significant variation in the melting temperatures for the different cells containing 7N gallium. The melting temperature of the 5N's samples from Lot No. 3792 is only slightly lower than the average for the 7N's samples; in contrast, the samples from Lot No. 1226 melt nearly 0.001 °C lower. Presumably, this is the effect of the higher content of copper detected in the material from Lot No. 1226. It appears, therefore, that the observed melting temperature is very sensitive to small concentrations of copper. Cell G59A5 was a glass cell with a nylon well. This cell was used in the preliminary study and became contaminated with both oil and air as a result of the nearly inevitable cracking of the cell during freezing. In this case, the cracks were simply covered with epoxy cement and the cell used despite the contamination. Thus, it appears that the presence of oil and oxide, if any of the latter formed, has little effect on the melting curve, as would be expected if both were insoluble in the metal. As regards the oxide, Roeser and Hoffman (5) also noted that its presence seemed to have no noticeable effect on the melting point.

In placing an uncertainty on the temperature of the melting point, it is important to bear in mind that there are two principal sources of this uncertainty. The first is simply the uncertainty in determining a temperature on IPTS-68 by use of the thermistors. As previously discussed, this uncertainty is about 0.001 °C. A second source of uncertainty arises from not knowing how reproducible the melting point is. As a crude estimate of this, we use the standard deviation in the melting temperatures reported in Table 2; this is 0.0004 °C. Because these two uncertainties are nominally unre-lated, we add them to obtain an estimate of the uncertainty of reproducing the gallium melting point on IPTS-68. Thus, we find the melting temperature of 7N's pure gallium on IPTS-68 to be $29.771_1 \pm 0.001_1$ °C. It is, however, quite possible that some of the scatter in the values of the melting point simply reflects the random errors arising from instrumentation and calibration. In this case, the uncertainty would be somewhat less. With the results presented here, we cannot resolve this question.

In conclusion: I found the melting point of gallium to be nearly ideal as a temperature reference point for clinical laboratories. The indicated melting temperature of 29.771_1 °C changes by less than 0.0005 °C during several hours and reproduces from day to day and cell to cell with a precision of better than 0.001 °C. The cells themselves are simple and economical to construct, and the melting procedure is very straightforward. It seems likely that the gallium point may, in fact, be suitable as either a secondary or primary reference point of the next International Practical Temperature Scale.

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The Gallium Melting-Point Standard: Its Role in Manufacture and Quality Control of Electronic Thermometers for the Clinical Laboratory

Henry E. Sostman

I discuss the traceability of calibration of electronic thermometers to thermometric constants of nature or to the National Bureau of Standards, from a manufacturer's basic standards through the manufacturing process to the user's laboratory. Useful electrical temperature sensors, their advantages, and means for resolving their disadvantages are described. I summarize our development of a cell for realizing the melting phase equilibrium of pure gallium (at 29.770 °C) as a thermometer calibration fixed point, and enumerate its advantages in the routine calibration verification of electrical thermometers in the clinical chemistry laboratory.

Electronic thermometers in which small and fast-responding thermistors are used as temperature sensors provide a valuable addition to the temperature-measuring capability of the clinical laboratory. The principal reason for this is that the thermistor thermometer's response to temperature is an electrical rather than a visual analog of temperature, which can be interfaced directly to a variety of important devices such as meters, recorders, data-loggers, controllers, and computers (1).

My purpose here is to familiarize the reader with some of the properties of thermistors and other electrical temperature sensors; to show how a manufacturer of electrical thermometers realizes, maintains, and transfers the International Practical Temperature Scale (IPTS) to the user of an electrical thermometer; and to discuss the important role that frequent calibration at the gallium melting point plays in establishing and maintaining the validity of that transfer.

Traceability

"Traceability" of calibration of a thermometer means the ability to demonstrate an unbroken sequence of

steps between the basic truths of the IPTS, through the manufacturing calibration process, through final inspection, to the thermometer in the laboratory of the user. The basic truths of the IPTS are the temperatures at which specific pure materials exhibit equilibrium between two or three phases. These equilibrium points, also called fixed points, provide calibration environments at precisely known and repeatable temperatures that are physical constants of nature.

The Metrology Standards Laboratory at Yellow Springs Instrument Co. (YSI) maintains 10 phase-equilibrium fixed points that permits calibration against constants of nature for a wide range of thermometers. None of these thermometric fixed points falls within the 20 to 40 °C range of clinical importance. The gallium point, at 29.770 °C (2), is the eleventh and latest fixed point to be added to this Laboratory's capability, and is now used routinely to assure measurements near the midpoint of the clinical laboratory range (3). Table 1 lists the complete series of fixed points maintained at YSI.

In addition to showing traceability of calibrations to constants of nature, it is also necessary to demonstrate traceability to the National Bureau of Standards (NBS). The YSI laboratory has two Standard Platinum Resistance Thermometers that meet the criteria for interpolation standards of the IPTS (4). These are transported to the NBS at regular intervals for calibration (5). They are then used to verify consonance between the thermometric fixed points maintained at the NBS and those at YSI. Resistance measurements of these standard thermometers are related to the NBS by calibrating the resistance-measuring bridges against standard resistors certified by the NBS.

The Metrology Standards Laboratory is in turn responsible for maintaining and certifying the calibration of all standards of temperature measurement used in the production, test, calibration, and inspection of YSI thermometers. For example, it is responsible for as-

suring the accuracy of the thermometer probes that control temperature within the specially-designed laminar-flow baths. Temperature gradients are known to be less than 0.001 °C in such baths and absolute temperature accuracy with respect to the IPTS is established with the Standard Platinum Resistance Thermometer traceable to the NBS. These special liquid comparison baths are used as mentioned in this paper (a) to determine resistance networks of probes at 0, 25, and 40 °C, in order to make them interchangeable, and (b) to establish the final product performance at 25, 30, and 37 °C after calibration at the melting point of gallium.

Types of Temperature Transducer Used in Electronic Thermometers

Several electrical properties of materials vary with temperature and can be used as the temperature-sensing principle of electronic thermometers. I will discuss three types of sensors: (a) thermocouples that change voltage and (b) platinum and (c) semiconductor thermistors; both of the last two change in resistance with change in temperature.

Thermocouples have been the mainstay of industrial temperature measurement for almost a century, although they are gradually being replaced in many applications by industrial platinum resistance thermometers. A thermocouple works in the following manner: when two conductors of dissimilar material are fused together to form a junction (called the "measuring junction") and the other ends are connected into a measuring system (called the "reference junction"), a small voltage is generated, which is related to the temperature difference between the two junctions (6, 7). Thermocouple pairs may be made of many materials and vary widely in temperature range and in linearity, stability, and outputs, and so afford the user much latitude in meeting the requirements of his work. Unfortunately, the electrical output is usually small. Also,

because the output is a function of the temperature difference between the measuring and reference junctions, it is necessary to know the temperature of the reference junction very accurately. Thermocouples can meet special needs in the clinical laboratory when very small size (wires as small as 0.012 mm in diameter) and very fast response (time constants in milliseconds) are necessary.

Standardized thermoelectric pairs are designated by letter identifications, and tables of thermoelectric voltage vs. temperature difference from the reference junction temperature have been published by the NBS (8) and others (6).

Two popular thermocouples are type E and type T. A type E thermocouple made of chromel wire and constantan wire is usable over a range from −270 to +1000 °C. It has the highest output of any standardized thermocouple: 61 μV per degree Celsius in the 20–40 °C range. A type T thermocouple made from copper wire and constantan wire is usable over the range −270 to +400 °C, and has an output of 41 μV/°C over the 20–40 °C range (8). It has the best accuracy specification, because of the high purity of the copper wire.

Platinum resistance thermometers depend upon the change in electrical resistance of pure platinum wire as a result of change in temperature. The Standard Platinum Resistance Thermometer is the designated interpolation instrument over a large portion of the IPTS (4). This laboratory standard, although an instrument of great sensitivity and stability, is large, delicate, and fragile, and requires complex and expensive auxiliary equipment. In general, its use is limited to standards laboratories. For the workaday purpose of many clinical-laboratory and industrial-control applications, smaller and more rugged platinum resistance thermometers have been developed, which retain the desirable attributes of platinum at some sacrifice in ultimate performance and are used in measurement and control systems requiring accuracy and stability over a wide temperature range in working environments (9).

Thermistor resistance thermometers, like platinum thermometers, exhibit a change in resistance with change in temperature, but they are made from semiconductor materials instead of pure metal wire. The usable range of thermistor thermometers is relatively narrow, but over this range they exhibit a very high sensitivity (change in resistance/change in temperature). This large rate of change simplifies the design of readout instrumentation for narrow temperature ranges.

Thermistors are made in many shapes and sizes, of several material formulations, and by several processes. Two types, however, are of primary importance in clinical temperature measurements: bead and disc thermistors (10, 11).

Bead thermistors may be thought of as single drops of material that are bridged across a pair of conducting wires and then furnace-fired into a bead of ceramic material. The bead diameter is typically 0.5 mm, but

may be as small as 0.1 mm. A typical permissible temperature range is −50 to +300 °C. Tolerances on resistance and the slope of the curve of resistance vs. temperature are typically wide, because the properties of the finished thermistor depend on the original material and the details of process, and no adjustment can be made during manufacture.

Disc thermistors are made from materials that generally are similar to those used in bead thermistors, but are stamped into pellets in a pill press, are sintered in furnaces, fitted with connecting wires, adjusted to specifications, and overcoated, typically with epoxy. The operating range may be −80 to +150 °C. Tolerances on resistance and sensitivity can be controlled within close limits in manufacturing; thus disc thermistors are closely interchangeable, while bead thermistors are not. The long-term stability of discs is not as good as that of the best beads.

Thermistor Sensors in Practicable Measurement Systems

For instruments intended for use over narrow temperature spans, such as those commonly used in clinical chemistry, the high sensitivity of thermistors is a compelling reason to use them as sensors. However, thermistors exhibit some less-desirable characteristics that must be mitigated or eliminated by design and calibration. In the discussion of these techniques, the example used will be a commercially-available temperature instrument designed for measuring temperature in spectrophotometer cuvettes.[1] The Cuvette Thermometer has five ranges, a survey range of 20 to 40 °C and four high-resolution ranges, 24 to 26 °C, 29 to 31 °C, 31 to 33 °C, and 36 to 38 °C. The specified accuracy of the high-resolution ranges is ±0.05 °C within 0.1 °C of center scale and ±0.1 °C over the rest of the scale, with readability of 0.01 °C and repeatability of 0.005 °C. Thermistor probes for the instrument are made to be interchangeable within these guaranteed limits by attention to the following:

1: Corrections to assure linearity and interchangeability. Figure 1 shows the curve of electrical resistance vs. temperature for the disc thermistor used as sensor for the Cuvette Thermometer. The complete curve is for the survey range of 20 to 40 °C; the shaded portions are the four high-resolution ranges. It is obvious that the slope of the line is different at the lower and upper end of the temperature range and also that the slope of each high-resolution range is different from that of the others.

Disc thermistors are adjusted in manufacture to an interchangeability of ±0.1 °C; bead thermistors cannot be adjusted, but must be selected for interchangeability.
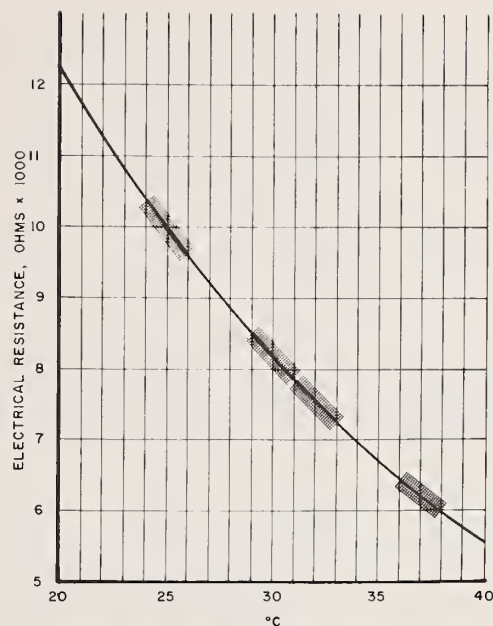
Fig. 1. Relationship between temperature and resistance of a typical disc thermistor over the range 20–40 °C, showing characteristic nonlinearity.

The range of the curve is the survey range of the Cuvette Thermometer. The four shaded portions are the four high-resolution ranges.

Neither type can be obtained with interchangeability sufficient to satisfy the final specifications for the Cuvette Thermometer. The problems of nonlinearity and of interchangeability are solved simultaneously by a resistive network built into the probe plug. Figure 2a shows a schematic of this network and Figure 2b shows the physical location of the resistors.

In the schematic, the resistor labeled R_T is the thermistor, and R_1, R_2, and R_3 are fixed resistors chosen to adjust the linearity and the interchangeability of the thermistors. In manufacture, each thermistor probe (without the network) is measured at 0, 25, and 40 °C in specially-designed laminar-flow baths whose temperature control and accuracy was discussed under *Traceability*.

On the basis of these measured values, R_1, R_2, and R_3 (which are to an extent interdependent) are calculated by a computer program to adjust the network to simulate the characteristics of a hypothetical nominal thermistor. The network makes the four high-resolution ranges exactly linear; and compensates for all but 0.2 °C of the nonlinearity of the survey range, which is compensated by use of a slightly nonlinear scale on that range only. The differences in slope of the four high-resolution ranges are corrected by use of the range-selection switch to slightly change the amplifier gain, so that all four high-resolution ranges can be displayed on the same scale.

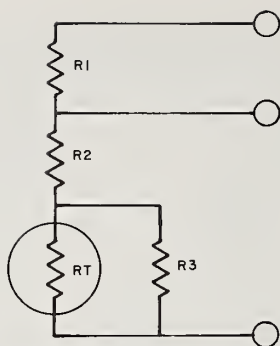*2: Correction for instability.* Thermistors are less

Fig. 2a. A resistance network for adjustment of linearity and interchangeability

Fixed precision resistors, selected by a computer program, adjust the thermistor R_T to nominal calibration and correct for the non-linearity shown in Fig. 1
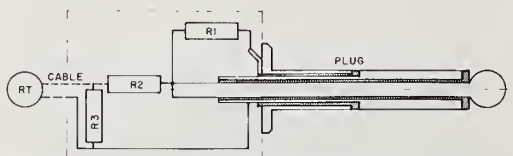

Fig. 2b. Physical location of adjustment resistor network

The plug has three electrical contacts, separated by insulation. The resistors R_1, R_2, and R_3 are shown as they are connected to the several conductors and are enclosed within the plastic handle of the plug. The cable extends from the handle to the thermistor R_T.

Fig. 3. Types of thermistor shift with age and use

stable over long periods of time than are platinum resistance thermometers, although they may be more stable than base-metal thermocouples. To study the stability of disc thermistors, five YSI probes made with disc thermistors were sent to the NBS for calibration at −40, 0, +40, and +70 °C, and the resistances were reported. These probes have subsequently been recalibrated at the NBS seven times between 1962 and 1975. The differences in resistance between 1962 and subsequent calibrations were converted to temperature. Table 2, line 1, shows the change from the 1962 initial calibration at +40 °C found upon each subsequent calibration; line 2 shows the change at 0 °C. It will be seen that the change at +40 °C is usually not the same as the change at 0 °C. Each shift contains two components: a *rotational* shift, or change in sensitivity, and a *translational* shift, or change in calibration that is the same at any temperature. Figure 3 clarifies the meaning of these terms. It is obvious that if the instrument has a means for adjusting the meter reading at one point, and the user has available one precise temperature standard at which to calibrate, the thermistor probe may be subjected to that precise temperature, and the adjustment may be used to eliminate the effect of translational shift. However, a calibration at one temperature cannot eliminate rotational shift.

Using the data of Table 2, one can eliminate the translational shift by subtracting Line 2 from Line 1 for each probe. This is 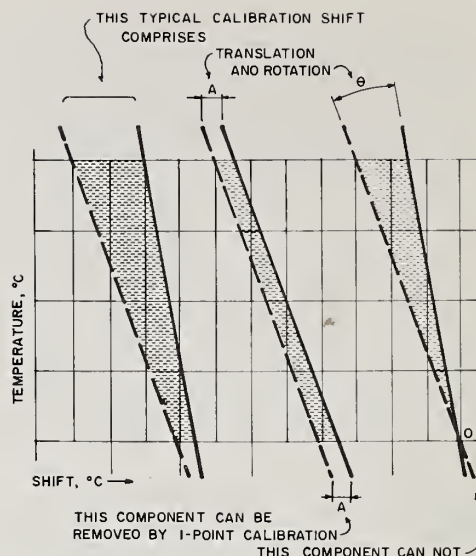the arithmetical analog of making an instrument calibration adjustment to shift the position of the pointer relative to the scale. The remaining shift, shown on Line 3, is the rotational shift between 0 °C and 40 °C, which cannot be eliminated by making a single calibration adjustment. However analysis of data at other temperatures shows that this rotational shift is essentially linear over this range, so that the rotational shift over the range from 20 to 40 °C will be ½ of the value shown on Line 3. Furthermore if a single calibration adjustment is made so that the instrument reading is correct at the middle of the 20 to 40 °C range, the calibration at 20 and 40 °C will be correct within ±½ the 20–40 °C error, or ±¼ of the value shown on Line 3. The value for the irreducible ± error over the range 20 to 40 °C for each of these probes is shown on Line 4.

This is an important statement, because it shows that errors due to thermistor shift can be reduced, by a single-point calibration near mid-scale, to insignificant errors over the entire 20–40 °C range.

3: Heat-extraction errors via connecting wires are analogous to stem-loss errors in liquid-in-glass thermometers, and are common not only to all thermistor thermometers, but to all electrical thermometers. This problem is resolved only by user understanding and care.

When a sensor, attached to connecting wires, is immersed into a temperature environment, heat flows from the warmer to the cooler end of the wires. The temperature depression of the sensing tip depends on (*a*) the temperature difference of the bath-to-ambient interface, (*b*) the distance from the sensing tip to that interface, and (*c*) the thermal conductivity and sectional area of the connecting wires. In one probe for the Cuvette Thermometer, a bead thermistor has connecting wires of 0.025 mm platinum–iridium, whose thermal

Table 2. Historical Shifts in Five YSI Thermistor Probes Calibrated at the NBS[a]

Line	Date calibrated	Temp, °C	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5
1	Jan. 1964	40	−0.027	−0.021	−0.023	−0.025	−0.017
2		0	−0.007	−0.006	−0.006	−0.005	−0.005
3			0.020	0.015	0.017	0.020	0.012
4			±0.005	±0.004	±0.004	±0.005	±0.003
1	Dec. 1964	40	−0.004	−0.017	−0.017	+0.002	−0.006
2		0	−0.003	−0.015	−0.028	−0.001	−0.000
3			0.001	0.002	0.011	0.001	0.006
4			±0.000	±0.001	±0.003	±0.000	±0.002
1	Jan. 1966	40	+0.001	−0.004	−0.029	+0.002	−0.002
2		0	−0.004	−0.003	−0.003	−0.003	−0.003
3			0.005	0.001	0.026	0.005	0.001
4			±0.001	±0.000	±0.007	±0.001	±0.000
1	Jan. 1976	40	−0.020	−0.025	−0.025	−0.014	−0.010
2		0	−0.004	−0.006	−0.018	−0.003	−0.006
3			0.016	0.019	0.007	0.011	0.004
4			±0.004	±0.005	±0.002	±0.003	±0.001
1	Dec. 1976	40	+0.023	+0.029	+0.002	+0.012	+0.008
2		0	−0.002	−0.002	−0.012	−0.002	−0.001
3			0.025	0.031	0.014	0.014	0.009
4			±0.006	±0.008	±0.004	±0.004	±0.002
1	Mar. 1970	40	−0.008	−0.016	−0.018	−0.008	−0.014
2		0	−0.001	−0.002	−0.010	−0.001	−0.003
3			0.007	0.014	0.008	0.007	0.011
4			±0.002	±0.004	±0.002	±0.002	±0.003
1	Nov. 1975	40	−0.018	−0.016	−0.018	−0.018	−0.024
2		0	−0.025	−0.025	−0.024	−0.020	−0.027
3			0.007	0.009	0.006	0.002	0.003
4			±0.002	±0.002	±0.002	±0.001	±0.001

[a] The initial calibration was made in January, 1962. Values shown below are differences in °C from the values of the initial calibration.
Note: All values in Lines 4 have been rounded off to the nearest 0.001 °C.

conductivity is 30 W/(m·K). In another, larger and more mechanically rugged probe, a disc thermistor has connecting wires of 0.21 mm copper, whose thermal conductivity is 410 W/m·K. Figure 4 shows the errors due to insufficient immersion for each of these probes. Stem-loss errors are relatively easy to evaluate in any given real situation. The sensor is gradually moved into the medium and the indicated temperature noted. When further immersion gives no continued change in indicated temperature, the immersion is sufficient. Such errors, where they occur in cuvette temperature measurements, can often be decreased or eliminated by coiling a few centimeters of wire inside the sample chamber.

Calibration of Thermistor Thermometers

A thermistor thermometer, like any other thermometer, is calibrated by exposing it to an accurately known temperature and noting the indication. In most electronic thermometers the meter pointer position can be adjusted while the probe is at a known temperature, to correct the indication. Thus, the accuracy of calibration is limited by the ability of the operator to adjust to the calibration mark and the accuracy of the calibration temperature. Calibration temperature environments are achieved by one of two means:

1: Stirred-liquid comparison baths allow comparison of a thermistor probe with a certified reference thermometer, which may be a Standard Platinum Resistance Thermometer or a precision mercury-in-glass thermometer (*12, 13*). Many journal articles and special publications adequately cover the techniques for such comparison methods (*14–16*); for example, the National Committee for Clinical Laboratory Standards, a voluntary national consensus standards organization, has recently published a Tentative Standard (No. TSI-2) entitled "Standard for Temperature Calibration of Water Baths, Instruments, and Temperature Sensors"

(17). This standard was prepared to "provide the necessary background information and methodology for the performance of practical temperature calibrations using Standard Reference Material (SRM) thermometers available from the NBS, Washington, D. C., and from commercial sources." By observing proper precautions, some of which are peculiar to the use of mercury-in-glass thermometers (18), it is possible to make comparison calibrations between these NBS reference thermometers (SRM 933 and 934) and thermistor probes that are traceable and accurate to IPTS-68 to ±0.03 °C at 25, 30, and 37 °C (12), but one cannot go below these levels of certainty, owing to certification limits and scale resolution.

The SRM 933 and 934 thermometers were an important interim step toward accurate and traceable calibration of clinical laboratory thermometers. However, it must be realized that they are not primary temperature standards, but rather only a means of transferring temperature standards; that is, they do not represent facts of nature, but simply transfer to the user's laboratory the standards that are based on the facts of nature as established at the NBS. Therefore all mercury-in-glass thermometers require periodic verification against the ice point or some other more primary temperature standard to assure their constancy and accuracy (12–16).[2]

2: Fixed-point temperature standards. The temperatures at which pure materials exist in two- or three-phase equilibrium are, on the other hand, fundamental constants of nature. First-order phase transitions (those that involve latent heat) occur at unique temperatures and can provide stable and primary environments for thermometer calibration (19). The IPTS defining fixed points and secondary reference points have already been discussed in Mangum's paper of this series (20) and some have been listed in my Table 1. However, these phase equilibria of pure materials are so fundamental to high-accuracy thermometry that a brief review is in place here.

The thermal condition in which pure water can exist simultaneously in its liquid and solid form at its own

[2] The equipment, skill, and time needed to make such comparisons is often grossly underestimated. To make comparison calibrations which approach ±0.01 °C, numerous sources of error listed in references 11–15 must be considered. For example, the following are frequently overlooked: (1) *Ice-bath verification of scale at 0 °C.* It is not generally appreciated how difficult it is to use an ice bath correctly. Errors due to failure to maintain a homogeneous slurry, to assure air saturation, and to keep it fresh (an ice bath immediately begins to dissolve CO_2 from the air) may result in icepoint depressions as large as 0.01 °C. (2) *Time constant errors.* The response to temperature change of head and disc thermistors is many times faster than that of mercury-in-glass thermometers. In a temperature bath in which the bath-medium temperature fluctuates randomly or cyclically, the thermistor probe may follow the changes while the SRM thermometers integrate them, and temporal differences of indication may he observed. One solution is to hang in the bat' n integrating block of copper or aluminum, with holes filled with le bath medium into which the reference thermometer and the thermistor can both he inserted to their proper immersion depths.
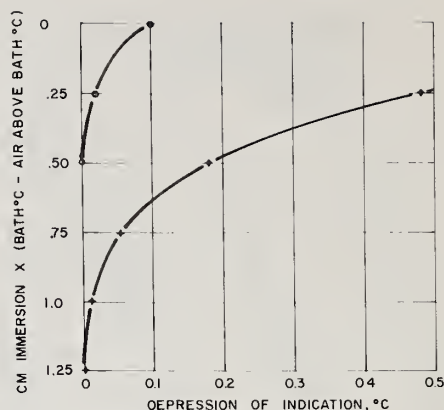
Fig. 4. Immersion errors for two types of thermistor probe and lead wire

Thermistor connecting wires will cause errors by extracting heat unless immersion depth is adequate. (*Top curve:* 4501 probe (bead); *bottom curve:* 4502 probe (disc))

vapor pressure, the "triple point," is defined as 273.16 K and 0.01 °C. It can be maintained for days or longer and realized to within 0.0001 °C once the initial strain-free equilibrium is reached. The thermal condition in which pure water can exist simultaneously in liquid and solid form, the ice point, is defined as −0.01 °C below its triple point; and that in which it can exist simultaneously in its liquid and vapor form at (1 standard atmosphere of ambient pressure), the boiling point, is defined as 373.15 K or 100 °C (4).

Other temperatures are defined by the liquid–solid equilibria of high-purity metals such as tin (231.9681 °C) and zinc (419.58 °C). In suitable but relatively simple equipment such phase equilibria may be maintained for many hours with temperature plateaus constant to 0.001 °C (4).

Gallium Phase-Equilibrium Studies and Applications

In 1973, in an attempt to discover such a fixed-point temperature standard in a range useful in clinical laboratories, we undertook a study of the liquid–solid equilibrium temperature of pure gallium. We sought to determine what that temperature is, and to describe techniques for maintaining it for long enough to permit practicable thermometer calibration. Other workers have reported similar efforts; Mangum's paper in this series contains a list of references (20). We have published our work elsewhere (2) and will only summarize some of its key features before discussing its application to clinical thermometers.

We obtained gallium metal from two sources. In each sample the purity of metal was stated by the manufacturer to be 99.9999% ("6N") pure gallium. Purity of a metal influences the temperature at which it melts, and also the sharpness of the melt plateau. These effects of increasing purity of gallium are discussed by Thornton in a prior paper in this series (21).

Table 3. Accuracies Found for 20 Disc Thermistor Probes before and after Calibration at the Gallium Point[a]

Probe No.	Col. 1 29.770 °C (gallium)	Col. 2 Error, °C	Col. 3 25.000 °C	Col. 4 30.000 °C	Col. 5 37.000 °C
1	29.760	−0.010	24.995	30.000	37.010
2	29.770	0	24.995	30.000	37.005
3	29.765	−0.005	24.995	30.000	37.005
4	29.770	0	24.995	30.000	37.005
5	29.775	+0.005	25.000	30.000	37.000
6	29.775	+0.005	24.995	30.000	37.005
7	29.770	0	25.000	30.000	37.000
8	29.765	−0.005	24.995	30.000	37.005
9	29.790	+0.020	25.000	30.000	37.000
10	29.775	+0.005	25.000	30.000	37.000
11	29.775	−0.005	25.000	30.000	37.000
12	29.770	0	25.000	30.000	37.000
13	29.775	+0.005	25.000	30.000	37.000
14	29.770	0	24.995	30.000	37.005
15	29.770	0	25.000	30.000	37.000
16	29.775	0	24.995	30.000	37.005
17	29.765	−0.005	24.995	30.000	37.005
18	29.765	−0.005	24.995	30.000	37.010
19	29.760	−0.010	25.000	30.000	37.000
20	29.765	−0.005	24.995	30.000	37.005

[a] Note: Each of 20 probes were plugged into the readout instrument and the instrument zero adjusted according to the instruction manual. The probes were then used to measure the gallium point, and the indicated temperature and error are shown in columns 1 and 2, respectively. The instrument was then adjusted to show the gallium point correctly for each probe, and the probes were subjected to 25, 30, and 37 °C in stirred baths. The indications obtained are shown in columns 3, 4, and 5.

To establish the melt temperature for 99.9999% pure material, we made repeated measurements with our NBS-traceable Standard Platinum Resistance Thermometers. Two large polypropylene cells were constructed, each containing 500 g of gallium from a different source. These large cells were necessary to obtain sufficient immersion depth and mass of metal around the temperature-sensing element of the Standard Platinum Resistance Thermometers. The melt equilibrium temperature of each cell was measured five times with each of our two standard thermometers. The calibration of each thermometer was verified at the triple point of water before and after each set of measurements. The mean and standard deviation for 10 measurements (five with each of two thermometers) for each of the two cells were (a) 29.7695 ± 0.0012 °C and (b) 27.7696 ± 0.0009 °C. We therefore reported (2) that the melting equilibrium temperature of gallium of this purity is 29.770 °C, with an uncertainty of ±0.002 °C on IPTS-68. An atmospheric pressure effect of 0.0015 ± 0.0005 °C per standard atmosphere (101 kN/m^2) was determined during these measurements.

The duration of the constant-temperature melt plateau of these large cells was found to be 19, 31, and 68 h when the water bath was set 0.3, 0.2, and 0.1 °C, respectively, above the melt temperature. Small cells containing 40 g of gallium of the same purity had pla-

teau durations of 7.5, 12, and 26 h at the same bath elevations.[3]

Quality Control of Thermistor Thermometers

Smaller gallium melting-point cells containing 40 g of 99.9999% pure metal were constructed with central wells of 3.5 mm inside diameter for the insertion of thermistor probes, either bead thermistors (Model 4501) or disc thermistors (Model 4502). Using these cells, we tested 20 probes, representing a production run of Model 4502, for conformity to specification. A YSI Model 45CU Cuvette Thermometer was operated in accord with the Instruction Manual on the 29–31 °C high-resolution range. Each probe was inserted in turn

[3] While the gallium point can be realized by chilling the metal to its solid phase and then heating to slightly above the melt temperature in a stirred liquid bath, some skill and awareness of possible problems is nevertheless required. It is an attractive idea to contemplate an automated device for routine daily use by laboratory personnel that would remove these problems. A relatively straightforward device can be imagined in which the cell is mounted in a block that is heated and cooled either as a function of elapsed time or of thermal profile, to provide the thermal cycle required to realize the melt plateau without operator attention. It should be possible to turn on such a device with a timer, or at the beginning of the working day, and have available all day a fundamental temperature reference at 29.77 °C, accurate within a few thousandths of a degree. We have such a device under development and it will be available, it is hoped, in the fall of 1977.

into the gallium cell at its melting equilibrium point and the meter indication noted. Column 1 of Table 3 shows the results obtained. It will be noted that while the instrument's accuracy specification is ±0.1 °C at 29.77 °C (±0.05 °C within 0.1 °C of center scale, which for this range is 30 °C) the twenty probes in one electrical thermometer displayed errors at 29.77 °C of only −0.010 °C and +0.020 °C or less.

Accuracy at 25, 30, and 37 °C after Adjustment to Gallium

Each probe in turn was inserted into one of the small 40-g gallium cells maintained at its melting equilibrium point. The Model 45CU Cuvette Thermometer was adjusted, using its zero-adjustment knob, to display exactly 29.77 °C on its indicating meter. Following this adjustment at the gallium point it may be stated that the instrument is traceable to IPTS-68 at this one point by the work previously described (2).

Each probe, while connected to the calibrated system, was then placed in sequence into stirred calibration baths at 25, 30, and 37 °C and the indications noted (bath control and accuracy described under *Traceability*). These indications are shown in Columns 3, 4, and 5 of Table 3. It will be seen that errors at 30 °C could not be detected, while at 25 °C the largest error noted was −0.005 °C and at 37 °C the largest error noted was +0.010 °C.

In summary, thermistors, because of their high-resistance change per degree Celsius near ambient temperature, provide a rapidly responding and relatively stable temperature transducer for electronic thermometers. By frequent calibration at the gallium melting equilibrium temperature in an appropriate cell, the user of electronic thermometers with thermistor probes can calibrate them at 29.77 °C to ±0.01 °C, with traceability to IPTS-68. This calibration to a constant of nature represents standardization at the center of the range of temperatures of interest within the clinical laboratory.

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The Gallium Melting-Point Standard: Its Application and Evaluation for Temperature Measurements in the Clinical Laboratory

George N. Bowers, Jr. and Stanford R. Inman

We are impressed with the ease and certainty of calibrating electronic thermometers with thermistor probes to ±0.01 °C at the gallium melting point, 29.771_4 °C. The IFCC reference method for measuring aspartate aminotransferase activity in serum was run at the reaction temperature of 29.771_4 °C. By constantly referencing to gallium as an integral part of the assay procedure, we determined the absolute reaction temperature to IPTS-68 (International Practical Temperature Scale of 1968) to ±0.02 °C. This unique temperature calibration standard near the center of the range of temperatures commonly used in the clinical laboratory is a valuable addition and can be expected to improve the accuracy of measurements, especially in clinical enzymology.

Over the past two decades, we have been concerned with the accuracy and control of temperature(s) used in clinical laboratory testing, particularly the reaction temperature(s) in clinical enzymology (1–4). As explained in a preceding paper (5), temperature measurements, to be considered accurate, must be traceable either directly or by interpolation to the *defining fixed points* or *secondary reference points* of the International Practical Temperature Scale of 1968 (IPTS-68). In this laboratory, traceability to IPTS-68 was achieved before 1974 by sending a suitable mercury-in-glass thermometer to the National Bureau of Standards (NBS) for calibration (6), since 1974 by use of the clinical Standard Reference Materials 933 and 934 (7).

In September 1976 we started an evaluation of a small prototype gallium melting-point cell,[1] which was designed specifically to aid in the calibration of small thermistor probes of electronic thermometers (8). This paper describes some of our studies with this prototype gallium cell, especially as they relate to the accurate determination of the final reaction temperature for reference methods in clinical enzymology.

Calibration of an Electronic Thermometer and Its Probes

Prior "in-house" calibrations for two identical electronic thermometers in various combinations with four bead-thermistor type probes,[2] as judged from comparisons in stirred liquid baths with use of SRM's 933 and 934 mercury-in-glass thermometers as the reference thermometers, had given an uncertainty at 25, 30, and 37 °C of ±0.03 °C (7).

Table 1 shows our "in-house" calibrations for the same two electronic thermometers in various combinations with the same four bead-thermistor probes, but with use of the liquid–solid equilibrium temperature of the NBS prototype gallium cell. In adjusting the electronic thermometers, we exactly followed the instruction manual and then switched to the 29 to 31 °C high-accuracy range. With the bead thermistor of the probe deeply immersed within the well of the gallium cell, the fixed point of the gallium melt was then judged visually from the meter's dial. The IPTS-48 dial readings of the Yellow Springs Instrument Co. thermometers were converted to IPTS-68 by making a correction of −0.0093 °C.[3] As Table 1 shows, probes No. 157 and 178 seemed to calibrate nearest to 29.77 °C (IPTS-68) with both electronic thermometers. Note that the calibrations of all probes, whether performed by one of us (G.N.B.)

after only a few hours' experience with the gallium cell or three months later by S.R.I. after much greater experience, were repeatable to within 0 to ±0.01 °C. Furthermore, no readings of the probes at the 29.771_4 °C gallium reference point were found to be beyond the manufacturer's claims of "readability of ±0.01 °C with absolute accuracy of ±0.05 °C with NBS traceability."

The complex corrections due to the nonlinearity of response that are inherent in most thermistors must be understood and clearly defined for the average user before the certainty of calibrations at the melting point of gallium, 29.771_4 °C, can be used to judge accuracy as one moves to more distant temperatures, i.e., 25 or 37 °C. As Sostman has suggested in the preceding paper (9), the uncertainty at 30 °C is also ±0.01 °C, once the calibration at 29.77 °C is made. The move to another, more-distant temperature requires switching to another "high-accuracy range" setting, and therefore increases the uncertainty; yet, surprisingly, Sostman's data at 25 and 37 °C show no probes to be beyond ±0.01% (see Table 3 of ref. 9). As good as these results are, the fact remains, nevertheless, that one-point calibration of thermistors can never be as sure as two- or three-point checks. The need within the clinical laboratory community for other, more distant fixed points, particularly in the range of body temperature from 36 to 38 °C (or even to 40 °C) is all too obvious, not only for calibrations of fever thermometers but also for critical tests such as blood gases and pH determinations.

Stability of Measuring System

The combination of a Yellow Springs Instrument Co. electronic thermometer and a strip-chart recorder[4] is used in our laboratory to measure temperature in the 1.0 to 3.0 ml volumes of the final reaction mixtures used for enzyme assays. We sought to understand the inherent sensitivity and stability of this system by expanding and recording the signals given with the probes in the gallium cell. Representative recorder tracings of temperature response vs. time for the various component parts of this "expanded" system are given in Figure 1. The recorder in these studies was adjusted to equal 0.10 °C full scale (250 mm) when the high-accuracy range switch of the Yellow Springs Instrument Co. electronic thermometer No. 135 was set to the 29–31 °C position. Each 1 mm of chart space was therefore equal to 0.0004 °C, giving an expansion of 50-fold over the dial scale. The noise and drift of the various components listed in the legend of Figure 1 were studied. These recorder tracings reveal that the resolution of the gallium melting-point temperature (Figure 1C) in this measuring system is limited by the noise associated with the electronic thermometer's circuitry (Figure 1B). By estimating a center line between the extremes of the noise amplitudes at the beginning and at the end of a half-

Table 1. Calibration of Two Electronic Thermometers and Four Probes

	Thermometer No. 146 with probes no.			
	157	159	178	230
Mode/operator/month	Temp, °C			
Visual[a]/C.N.B./Sept.	29.76	29.75	29.77	29.73
Visual[b]/S.R.I./Dec.	29.76_5	29.75_5	29.77_0	29.72_5

	Thermometer No. 135 with probes no.			
	157	159	178	230
Mode/operator/month	Temp, °C			
Visual[a]/G.N.B./Sept.	29.76	29.75	29.77	29.73
Visual[b]/S.R.I./Dec.	29.77_0 set to	29.75_5	29.77_5	29.73_0
Recorder[c]/S.R.I./Dec.	29.771_4	29.751_5	29.781_5	29.731_5

[a] Only to 0.01 °C.
[b] Estimated to nearest 0.005 °C.
[c] Estimated from chart to nearest 0.0005 °C with probe No. 157 set to 29.771_4.

hour's tracings, we could show that the drift in each tracing (A, B, and C) was less than ±0.001 °C/h.

Using this stable expanded system again with electronic thermometer No. 135, we restudied the four probes to document more carefully any differences between them. Probe No. 157 was arbitrarily set equal to 29.771_4 °C. Note how closely the data from these expanded studies paralleled, both in sign and in magnitude, those obtained by the simpler direct visual readings of Table 1.

The sensitivity and stability of this expanded system to gallium has also been used in turn to study the cycling characteristics and the accuracy of the set-point of the temperature control block on an automated enzyme analyzer.[5] As shown in D of Figure 1, the thermoelectric heat pump controlling this block completes a heat/cool cycle every 12–15 s, with amplitudes of ±0.003 °C around an exceedingly stable set-point. As shown in E and F of Figure 1, we have used the gallium fixed point to adjust the block to exactly 29.77 °C. As shown in Table 2, repeated checks of this control block's set-point temperature during several weeks have shown no change from 29.77 °C beyond ±0.01 °C.[6]

Other studies to determine the exact temperature of the reaction mixture within the cell in the KA-150 vs. the temperatures of its spectrophotometric metal-walled cuvette and the control block are in progress in order to understand and control the various sources of

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[4] Model 7100 BM (Hewlett-Packard Co., Palo Alto, Calif. 94303), with the following specifications: linearity 0.2% min, dead band 0.1%, max. response time 0.05 full-scale, accuracy 0.2% full-scale.

[5] Model KA-150 Kinetic Analyzer; Perkin-Elmer Corp., Norwalk, Conn. 06856.
[6] Neither Figure 1 nor Table 2 is intended to show that the temperature of the final reaction mixture in the KA-150 cell is known or controlled to such narrow limits.
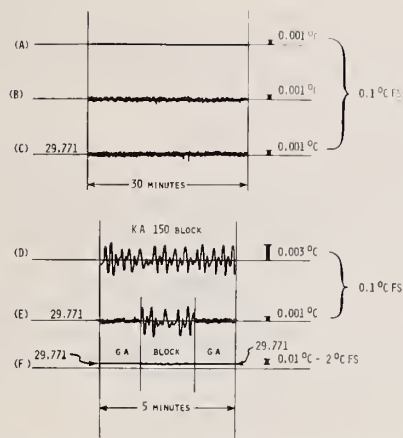
Fig. 1. Recordings of temperature vs. time in a study of electronic thermometers and probes calibrated with the gallium melting point standard

The recorder's full scale (250 mm) was made equal to 0.1 °C. (A) Recorder alone with input shorted out (pen width, about 0.7 mm = 0.0003 °C). (B) Recorder plus electronic thermometer No. 135 (set to 1.0 with 1.0 ADJUST control). (C) Complete system with probe No. 157 placed into the NBS gallium cell No. G79A2 at 29.7714 °C. (D) KA-150 thermoelectrically controlled block. (E) Setting mid-point of block cycles to 29.77 °C with aid of gallium. (F) Same as E, but full-scale = 2 °C between 29 and 31 °C.

heat additions and losses. Frequent calibration of those tiny thermistor sensors at the gallium melting point assures us that the work is accurate and traceable to IPTS-68. Thus, in addition to serving as an accuracy standard for calibration purposes, a gallium cell provides an extremely useful temperature fixed-point from which to make pragmatic comparison of electronic noise levels, sensitivity, and stability on our equipment.

Reaction Temperature and Analytical Variability

The profound effect that unrecognized reaction temperature changes can have on analytical variability in clinical enzymology has recently been re-emphasized in the clinical chemical literature (10, 11). Results of a large survey conducted by the Center for Disease Control (CDC) show that there is great intralaboratory variability in measuring the activity of aspartate ami-

Table 2. Stability of KA-150 Control Block during Six Weeks as Judged with Visual Reading

1976	Reading
12/3	29.77_5
12/6	29.77_5
12/7	29.77_5
12/14	29.77_5
12/23	29.77_0
12/30	29.77_0
1977	
1/4	29.77_5
1/18	29.77_0
1/21	29.77_0
1/25	29.77_0

notransferase (EC 2.6.1.1) in serum, even when an identical reaction temperature is said to have been used (12). Our review of these data for this enzyme shows that the mean activity reported at 37 °C divided by the mean at 30 °C [$\bar{x}$ U/liter at 37 °C/$\bar{x}$ U/liter at 30 °C] gives a "temperature factor" ranging from 1.38 to 1.44 for each of the four high-purity stable samples of aspartate aminotransferase. However, intensive study of these same samples at both 30 and 37 °C, in order to define in greater detail the temperature/activity relationship, gave a "temperature factor" of 1.52 in three laboratories in which special attention was given to controlling the reaction temperatures as accurately as possible.[7] This 1.52 "temperature factor" found on these high-purity, well-characterized reference materials was in agreement with the value calculated from the Arrhenius plots published by Rej et al. (13). This "apparent" lowering of the "temperature factors" suggests that the reaction temperatures might well be somewhat different from the 30 or 37 °C reported. It is well recognized that many other methodologic factors besides temperature (e.g., substrate concn.) could also contribute to these differences. However, to decrease the analytical variability of aspartate aminotransferase measurements in routine daily assays to <±2% due to temperature considerations alone, a goal for reaction temperature accuracy and control must be set at ±0.1 °C at both 30 and 37 °C.

Recommendations for reference methods in clinical enzymology deliberately seek to minimize temperature as a source of serious analytical variability. However, it can be shown that even the tight specifications for temperature as proposed by the Expert Panel on Enzymes of the International Federation of Clinical Chemistry (IFCC) can contribute an uncertainty of about ±0.5% to the analytical variability of the final measurement (4). Figure 2 shows activity of aspartate aminotransferase as a function of reaction temperature near 30 °C for the well-characterized aspartate aminotransferase from erythrocyte cytoplasm described by Rej et al. (13). We determined this slope by measurements at 25 and 30 °C, and using the provisional recommendations for the IFCC Reference Method for aspartate aminotransferase (14). In Figure 2 the wider vertical bar centered on 30 °C graphically depicts the accuracy limits for the reaction temperature recommended for reference methods by the IFCC's Expert Panel on Enzymes (4). This specification for accuracy to IPTS-68 at the 30 °C set-point is given as ±0.05 °C. Thus two laboratories might vary in set-points by 0.1 °C yet still be within specifications. As shown, these extremes of the temperature limits around 30 °C intersect the slope of the plot of activity vs. temperature to give a potential variability (A of the top set of horizontal lines) between two laboratories which could reach
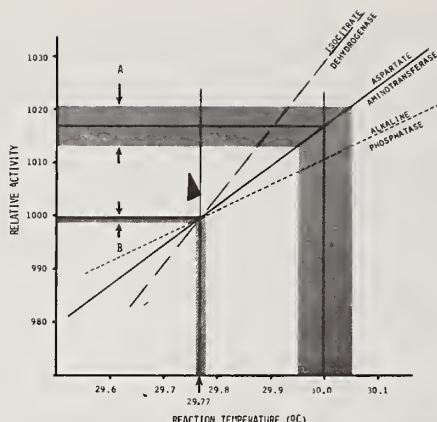
735

Fig. 2. Change in enzyme activity vs. reaction temperature
The *shaded vertical bars* at 30 ± 0.05 °C and 29.77 ± 0.01 °C represent written specifications for accuracy and precision of reaction temperature for IFCC and for gallium, respectively. The resulting maximum variability in activity owing to these temperature specifications is represented by *A* (8/1000) and *B* (1.6/1000). Note that each enzyme's activity/temperature plot varies, as shown by the plot for alkaline phosphatase (*dotted*) and isocitric dehydrogenase (*dash*)

as high as eight parts per 1000, or about 1%. Also in Figure 2, the dotted line for alkaline phosphatase (EC 3.1.3.1) and the dashed line for isocitrate dehydrogenase (EC 1.1.1.42) show that variability in activity due to temperature changes alone may be as low as five parts per 1000 (in the case of alkaline phosphatase; see ref. *3*) or as high as 20 parts per 1000 (in the case of isocitrate dehydrogenase; see ref. *2*), depending upon the enzyme being studied.

The reaction-temperature accuracy and precision specifications for reference methods were written by the members of the IFCC Expert Panel in 1972, when traceability to IPTS-68 at 30 °C was difficult to achieve (*4*). Despite the introduction in 1974 of certified Clinical Standard Reference Materials Nos. 933 and 934, designed in part to help improve clinical enzymology by providing calibrations at 25, 30, and 37 °C certified to ±0.03 °C, it is still extremely difficult to be certain that the reaction temperature is indeed 30.0 °C within the 1.0 to 3.0 ml of the final reaction volumes. This is mainly because of the size and heat capacity of mercury-in-glass thermometers, which preclude their direct use in small volumes of reaction mixtures. As important as these SRM's 933 and 934 are, it is difficult to anticipate any large network of laboratories achieving these IFCC temperature specifications by use of mercury-in-glass thermometry alone.

Fortunately, the introduction of the gallium melting-point standard and the availability of relatively stable and sensitive electronic thermometers with thermistor probes, greatly simplifies the problem of making accurate temperature measurements in small final reaction volumes. Furthermore, when the reaction temperature is made to correspond exactly to the gallium melting point, great simplification occurs. For example, the narrower set of vertical lines centered on 29.77 °C in Figure 2 represents our experience of the past few months and vividly illustrate the fact that point

calibration to gallium is easily achieved to ±0.01 °C. Therefore the temperature variability (*B* of the lower pair of horizontal lines) as related to *written* specifications can be reduced from 8 parts per 1000 to 1.6 parts per 1000 by this one move alone.

The ease and certainty of operationally achieving the temperature of 29.77 ± 0.01 °C by use of the gallium melting-point standard, suggests that even a large network of laboratories, either nationally or internationally, can be pulled together easily and quickly to achieve remarkable accuracy of reaction temperature at 29.77 °C. The slight decrease in total enzymatic activity at 29.77 vs. 30.00 °C is negligible in comparison to the advantages gained by point calibration to this unique constant-of-nature.

A Reference Method Run at 29.77 °C

We have experimentally improved the certainty of our reaction temperature measurements for the IFCC Reference Method for aspartate aminotransferase (*14*) by pragmatically using a gallium melting-point cell *as an integral and concurrent part of the method.* The gallium cell is placed in a water bath, which is initially controlled to about 0.15 °C above 29.77 °C. The bath circulates water, *first* to a jacketed rectangular quartz cuvette[8] and *then* (in series) to the heat exchanger of the spectrophotometer's sample compartment.[9] The probe of the electronic thermometer/recorder system is repeatedly moved between the gallium cell and the enzyme reaction mixture in the cuvette as the temperature is continuously recorded with full-scale expansion equal to 2 °C between 29 and 31 °C, as shown in Figure 3. The recovery time—i.e., the time required for the slightly cooled 1 ml of reaction mixture to equilibrate after transfer from test tubes in the bath through cooler ambient air in a syringe and then into the jacketed spectrophotometric cuvette—is about 2 min. However, to avoid interference with the carefully timed spectrophotometric observations, which should start 60 s after initiation of the reaction and then be made every 30 s for 300 s, the thermistor probe is withdrawn when the operator observes that the temperature curve is rapidly ascending and then slowing as equilibration starts. During the period of the 10 spectrophotometric readings, the probe is placed back into the gallium reference cell and it is again returned to the reaction mixture after the last spectrophotometric reading is taken. From this final portion of the recorder tracing of the reaction temperature we graphically determine the temperature to the nearest 0.01 °C by comparison to the position of the adjacent "gallium" line. From time to time the water bath is re-adjusted ever so slightly to bring this final reaction temperature to rest as close as possible to that

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[8] Constant-temperature jacketed quartz cells No. 160 or 160B (Hellma Cells, Inc., Box 544, Borough Hall Station, Jamaica, N. Y. 11424).
[9] Cary Model 16 spectrophotometer, equipped with heat exchanger for sample compartment (Varian Associates, Palo Alto, Calif. 94303).
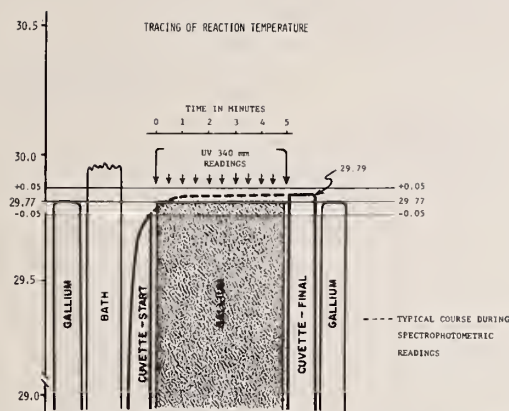
Fig. 3. Recording of temperature vs. time when gallium melting-point all at 29.771₄ °C is used as a part of the IFCC reference method for aspartate aminotransferase

of the gallium melting-point equilibrium temperature. Measurements of reaction temperature by this technique are not made beyond ±0.05 °C of the gallium reference point. We believe the *absolute* reaction temperature traceable to IPTS-68 within this reaction mixture is known to ±0.02 °C by this technique of concurrently referencing to gallium.

In conclusion, the ease of calibrating electronic thermometers and probes with the gallium melting-point standard at 29.771₄ °C is indeed remarkable. Furthermore, this calibration at 29.771₄ °C is accurate and traceable to IPTS-68 to ±0.01 °C. Similar accuracy through easy traceability of temperature to IPTS-68 awaits others who recognize and make use of the gallium melting-point standard. The gallium liquid/solid equilibration temperature is truly a fundamental constant of nature, well suited for use in clinical laboratory. The acceptance of the gallium melting-point temperature as the reaction temperature for the measurement of enzymatic activity by reference methods in clinical enzymology will help to decrease interlaboratory variability of results.

These improved measurements and control of the reaction temperature will in turn provide the basis for providing a sounder body of factual information upon which to develop national or international agreements concerning reference materials and methods in clinical enzymology.

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This Special Publication contains a series of papers published in Clinical Chemistry concerning our temperature measurement system, the gallium melting-point as a thermometric fixed-point, how the gallium melting-point fits into the measurement system, and applications of the gallium melting-point standard.

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