A UNITED STATES
DEPARTMENT OF
COMMERCE
PUBLICATION

NBS TECHNICAL NOTE 765

Low Temperature Thermometry: Interim Report

U.S.
EPARTMENT
OF
COMMERCE
National
eau
of
ds

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 Center for Computer Sciences and Technology, and the Office for Information Programs.

THE INSTITUTE FOR BASIC STANDARDS provides the central basis within the United States of a complete and consistent system of physical measurement; coordinates that system with measurement systems of other nations; and furnishes essential services leading to accurate and uniform physical measurements throughout the Nation's scientific community, industry, and commerce. The Institute consists of a Center for Radiation Research, an Office of Measurement Services and the following divisions:

Applied Mathematics — Electricity — Mechanics — Heat — Optical Physics — Linac Radiation [2] — Nuclear Radiation [2] — Applied Radiation [2] — Quantum Electronics [3] — Electromagnetics [3] — Time and Frequency [3] — Laboratory Astrophysics [3] — Cryogenics [3].

THE INSTITUTE FOR MATERIALS RESEARCH conducts materials research leading to improved methods of measurement, standards, and data on the properties of well-characterized materials needed by industry, commerce, educational institutions, and Government; provides advisory and research services to other Government agencies; and develops, produces, and distributes standard reference materials. The Institute consists of the Office of Standard Reference Materials and the following divisions:

Analytical Chemistry—Polymers—Metallurgy—Inorganic Materials—Reactor Radiation—Physical Chemistry.

THE INSTITUTE FOR APPLIED TECHNOLOGY provides technical services to promote the use of available technology and to facilitate technological innovation in industry and Government; cooperates with public and private organizations leading to the development of technological standards (including mandatory safety standards), codes and methods of test; and provides technical advice and services to Government agencies upon request. The Institute also monitors NBS engineering standards activities and provides liaison between NBS and national and international engineering standards bodies. The Institute consists of a Center for Building Technology and the following divisions and offices:

Engineering and Product Standards—Weights and Measures—Invention and Innovation—Product Evaluation Technology—Electronic Technology—Technical Analysis—Measurement Engineering—Building Standards and Code Services[4]—Housing Technology[4]—Federal Building Technology[4]—Structures, Materials and Life Safety[4]—Building Environment[4]—Technical Evaluation and Application[4]—Fire Technology.

THE INSTITUTE FOR COMPUTER SCIENCES AND TECHNOLOGY conducts research and provides technical services designed to aid Government agencies in improving cost effectiveness in the conduct of their programs through the selection, acquisition, and effective utilization of automatic data processing equipment; and serves as the principal focus within the executive branch for the development of Federal standards for automatic data processing equipment, techniques, and computer languages. The Center consists of the following offices and divisions:

Information Processing Standards—Computer Information—Computer Services—Systems Development—Information Processing Technology.

THE OFFICE FOR INFORMATION PROGRAMS promotes optimum dissemination and accessibility of scientific information generated within NBS and other agencies of the Federal Government; promotes the development of the National Standard Reference Data System and a system of information analysis centers dealing with the broader aspects of the National Measurement System; provides appropriate services to ensure that the NBS staff has optimum accessibility to the scientific information of the world, and directs the public information activities of the Bureau. The Office consists of the following organizational units:

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

---

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

[2] Part of the Center for Radiation Research.

[3] Located at Boulder, Colorado 80302.

[4] Part of the Center for Building Technology.

Low Temperature Thermometry: Interim Report

George Cataland and Harmon H. Plumb

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

NBS Technical Notes are designed to supplement the Bureau's regular publications program. They provide a means for making available scientific data that are of transient or limited interest. Technical Notes may be listed or referred to in the open literature.

U.S. DEPARTMENT OF COMMERCE, Frederick B. Dent, *Secretary*
NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, *Director*

Issued May 1973

National Bureau of Standards Technical Note 765
Nat. Bur. Stand. (U.S.), Tech. Note 765, 23 pages (May 1973)
CODEN: NBTNAE

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402
(Order by SD Catalog No. C13.46:765).
Price $0.40 domestic postpaid or $0.30 G.P.O. Bookstore.

FOREWORD

In the interest of informing the public on program developments and technical advances within the Division, we are increasing our publications activities, beyond the customary formal publication of complete pieces of work, through the media of NBS Technical Notes and NBS Reports. The former provide the means to deal with the subject matter at greater depth than normally tolerated by today's journal editors and the latter afford an opportunity to describe informally the progress toward current goals where the work is incomplete.

This is a progress report. The work is incomplete and is continuing. Results and conclusions are not necessarily those that will be included in the final, formal publications. The period covered herein is the calendar year 1972.

H. H. Plumb, Chief
Temperature Section
National Bureau of Standards

CONTENTS

Low Temperature Thermometry: Interim Report

George Cataland and Harmon H. Plumb

Earlier acoustical thermometer 'speed of sound' isotherms are compared with recent measurements. Where systematic deviations had appeared in "smoothing" through acoustically derived temperatures via germanium thermometers, a possible solution has emerged; more precise temperature control of the acoustical thermometer is desirable and has been realized. A cursory examination of the applicability of the Helmholtz-Kirchhoff equation was made with a modified sonic chamber. Measurements with the modified instrument have shown no changes in the experimental results.

The maintenance of the NBS P2-20 (1965) scale is described. A new calibration apparatus was constructed to accommodate more germanium thermometers thus reducing the calibration cost per thermometer during a calibration run.

Key words: Acoustical thermometer; calibrator; germanium thermometers; heat conduction; NBS P2-20 (1965) scale; 'speed of sound' isotherms; viscosity.

1. Introduction

A number of years ago the National Bureau of Standards Provisional Temperature Scale 2-20 (1965) was established; it was based upon acoustical thermometry and described in the literature [1]. Since that time the International Practical Temperature Scale of 1968 [2] was defined down to 13.8 kelvins and the NBS P2-20 (1965) has been used extensively not only within the United States but also by external research laboratories. The scale's widespread use has certainly been enhanced by the existence of a calibration facility [3] that could meet the requested calibration needs.

Although the low temperature scale met an immediate need for temperature determinations in the 2 to 20 K range, it was recognized that there were deficiencies in the acoustical thermometry from which the temperature determinations were derived and it was hoped that improvements could be made in the measurements and techniques of acoustical thermometry. This report will describe most of the continuing work, describe some of the problems that have been encountered, and indicate what may be the remaining program of measurements.

2. Speed of Sound in a Gas and Absolute Temperature

For clarity it is desirable to repeat some of the discussion that was previously presented [1].

When sound is propagated through a gas, if the frequency of the sound is not too high relative to the mean collision frequency of the gas molecules, the propagation is nearly adiabatic, and speed of sound [4,5] is

$$W = \sqrt{E/\rho} = \sqrt{\frac{-v^2}{M}\left(\frac{\partial p}{\partial v}\right)_S} = \sqrt{-\frac{C_p v^2}{C_v M}\left(\frac{\partial p}{\partial v}\right)_T} \qquad (1)$$

where ρ is the density of the medium of molecular weight M and E is the adiabatic bulk modulus defined by the relation

$$E = -v\left(\frac{\partial p}{\partial v}\right)_S = -\frac{C_p}{C_v} v \left(\frac{\partial p}{\partial v}\right)_T. \qquad (2)$$

The symbols v and p refer to the volume per mole and pressure of the medium, and the partial derivative is at constant entropy or temperature, as indicated; C_p and C_v are specific heats at constant pressure and volume, respectively. If the conducting medium were an ideal gas, its equation of state would be expressed by

$$pv = RT \tag{3}$$

and there would result

$$\left(\frac{\partial p}{\partial v}\right)_T = -\frac{RT}{v^2} \tag{4}$$

Additionally, the ratio of specific heats would be that of an ideal gas,

$$\left(\frac{C_p}{C_v}\right)_{\text{ideal gas}} = 5/3$$

(if the gas is assumed to be monatomic), and eq. (1) becomes

$$W_o^2 = \frac{5}{3}\frac{RT}{M}. \tag{5}$$

Equation 5 indicates the simple relationship between the absolute thermodynamic temperature T and the speed of sound in an ideal gas W_o. (The gas constant R and the molecular weight M are considered to be accurately known constants.)

In actuality an ideal gas does not exist, so eq. (5) must be modified for application to real gases. Of the two gases, ^{3}He and ^{4}He, which can be used for sound measurements at temperatures between 2 and 20 K, ^{4}He has been selected for experimental measurements. Its equation of state can be assumed to be represented by the empirical relationship [6]

$$pv = RT\left(1 + \frac{B}{v} + \frac{C}{v^2} \ldots\right) \tag{6}$$

where B and C are functions of the temperature called the second and third virial coefficients, respectively. If the quantity

$$\left(\frac{\partial p}{\partial v}\right)_T$$

is evaluated from eq. (6) and the ratio C_p/C_v is evaluated for the real gas, eq. (1) can be written

$$W^2 = \left(\frac{C_p}{C_v}\right)_{\text{ideal}} \frac{RT}{M}\left(1 + \alpha p + \beta p^2 + \ldots\right) \tag{7}$$

where

$$\alpha = \frac{1}{RT}\left[2B + \frac{4T}{3}\frac{dB}{dT} + (4/15)\,T^2\frac{d^2B}{dT^2}\right]. \tag{8}$$

β is a term that includes higher orders of the virial coefficients B and C. From eqs. (5) and (7) we obtain

$$W^2 = W_o^2\left(1 + \alpha p + \beta p^2 + \ldots\right). \tag{9}$$

It is now apparent that, if one determines an isotherm of W^2 as a function of pressure, the intercept W_o^2 of the extrapolated (to $p = o$) isotherm readily affords a means of calculating the isotherm temperature on the absolute scale. $W_o^2\,\alpha$ is the slope of the isotherm and there is no reason to assume that the slopes are not a smooth or continuous function of temperature.

In order to obtain values of the speed of sound as a function of pressure, one must determine the wavelength and the frequency. Several methods are possible but our work is based upon the creation of standing waves in a gas by means of an apparatus with a fixed frequency and a variable path. A quartz crystal, operating at its resonant frequency, radiates through ^{4}He gas to a reflector surface which is parallel to the quartz crystal; radiation is reflected back through the gas to the quartz crystal. If the spacing between the crystal and the reflecting surface is an integral number of half-wavelengths the helium gas will be in resonance and a peak voltage will be measured across the quartz crystal. The reflecting surface is displaced through detected integral numbers of half-wavelengths and its displacement measured. Thus λ is determined, the frequency of the quartz crystal is measured and, consequently, W can be calculated. This value of W is, of course, the phase speed corresponding to whatever mode exists in the tube of gas. It is supposed that this mode is sufficiently like the plane wave mode to allow identification of W, for our purpose, as the free-space value. The mode may not be pure but, if this is the case, its components are spaced so closely that the ultrasonic interferometer does not resolve them. The cavity that contains the ^{4}He gas is a right circular cylinder with an X-cut quartz crystal covering one end of the cavity and the reflecting surface of a piston, which can slide freely within the cylinder, nearly fills the other end of the cylinder. Provision is made for the gas space to connect to an external gas ballast volume and manometer. The resonating gas volume is maintained at the cryogenic temperature of interest but displacements of the piston's reflecting surface are measured at room temperature. A fused quartz rod extends from the piston through temperature gradients of a Dewar to ambient conditions and reliance has been placed upon the small value of the coefficient of expansion for fused quartz. More extensive details of the instrument and its operation appear in Metrologia [1].

3. Speed of Sound Isotherms 9 K to 21 K

A number of the isotherms upon which the scale NBS P2-20 (1965) were based did not appear to have been adequately characterized by fitting a linear function to the isotherm data. This is seen in table 1 where the experimental W^2 and p are listed for the 7 K, 8.1 K and 9 K isotherms. The Δ's for each isotherm indicate that there are systematic discrepancies between the actual data points and the assumed linear representation.

Table 1

T	$W^2 (m/s)^2$	P (Atmos)	Δ[a]	σ[b]
	30,980	.2017	5.0	
	30,818	.4076	- 3.0	
9.0 K	30,665	.6068	- 6.9	
	30,524	.8096	2.8	
	30,380	1.0005	2.2	5.6
	27,792	.1343	5.1	
	27,642	.2680	- 4.4	
8.1 K	27,466	.4380	- 2.0	
	27,287	.6090	- 2.3	
	27,120	.7740	3.5	4.8
	23,988	.1326	9.5	
	23,770	.2680	-10.1	
7.0 K	23,532	.4370	- 1.8	
	23,287	.6040	- 2.5	
	23,069	.7580	4.9	8.7

a. The columns under Δ contain the difference between the experimental W^2 at the indicated pressure and the W^2 of the linear function determined by the computer least squares fitting.

b. σ is the standard deviation in the least squares fitting of an isotherm.

Additionally, continued experimental experience indicated that some of the deviations, and the standard deviation σ (3.4 is approximately equivalent to 1 mK), were larger than might be associated with the inherent limitations of the measurements and the apparatus. The most probable causes of the observed systematic deviations appeared to be: that the linear representation covered a larger range of pressure than was applicable (the experimental data were not properly represented by just the linear term of eq. 9); or that the lowest pressure points were inaccurate because of experimental difficulties which one encounters in attempting to conduct measurements at low gas densities; operational problems involving the control of the experimental parameters (germanium resistance thermometry, frequency control, thermal equilibrium) might be improved upon.

It appeared that the range of linear representation might be the most significant cause of data misrepresentation so experimentation was initiated to determine acoustical isotherms at each kelvin from 9 to 21 kelvins and for pressure ranges that extended up to about two atmospheres. By these measurements we hoped to extend the pressure range for each isotherm to such an extent that significant curvatures would appear at the higher pressures; this would then be a guide that would be informative in determining the proper value of pressure for truncating the upper limit of pressure. The reason for conducting the experimentation between 9 and 21 kelvins, as opposed to below 9 kelvins, was that meetings of the Comité Consultatif de Thermométrie were to take place in the immediate future and we were desirous of making a contribution to the selection of thermometry fixed points in the liquid hydrogen temperature range. (At about the same time that these new acoustical measurements were being made, effort was diverted to conducting liquid hydrogen vapor pressure measurements). Another reason for initiating the higher temperature measurements was that the slope of the acoustical isotherms passes through zero at about 13.5 K and there was some question about the adequacy of previously determined isotherms in the vicinity of this temperature.

After identifying the pressure range for which the isotherms (at nearly integral temperature intervals) could be represented linearly, isotherms at half kelvin values, between 9 and 21 K, and at the triple and normal boiling points of equilibrium liquid hydrogen were measured. The experimental data and appropriate statistical information are given in table 2 for the triple-point-of-hydrogen isotherm.

Table 2

T	$W^2 (m/s)^2$	P (Atmos)	Δ	σ
13.8057	47808.70	.3743	- .208	
	47811.76	.4416	.191	
	47813.07	.5216	-1.66	
	47818.75	.5820	1.63	
	47820.94	.6624	.641	
	47823.13	.7325	.055	
	47825.32	.8029	- .544	
	47829.25	.8806	.319	
	47831.44	.9542	- .405	0.96

It is to be noted that the deviations, Δ, in table 2 are much more random than those of table 1. In addition, the standard deviation of the least squares fitting is much less than those of table 1. The standard deviations of the 13 and 14 kelvin isotherms that were reported earlier [1] were 5.4 and 8.3, respectively, and the Δ deviations exhibited systematic departures from linearity. The pressure ranges of the previously reported 13 and 14 kelvin isotherms extended from 0.4 to 1.4 atmospheres - obviously, this was too great a pressure range.

When the new isotherms from 9 to 21 kelvins had been determined it was appropriate to check them for consistency and smoothness. This was done in two ways. It was assumed that the resistance of a germanium resistance thermometer was a smooth function of temperature and subsequently the resistor was calibrated. Values of resistance were associated with the values of temperature that had been calculated for the new isotherms and the resistance-temperature values of the thermometer were computer fitted to a polynomial of the form

$$\log R = \sum_{m=o}^{n} A_n (\log T)^n$$

The results are given in table 3.

Table 3

Calibration of Germanium Thermometer 561

$T_{acoustic}$ (K)	R_{Ge} (Ω)	$T_{acoustic\ fitted}$ (K)	δT(mK)	$\frac{dR}{dT}$ (Ω/K)
8.9917	444.470	8.9914	-0.3	-133.2
9.4956	383.300	9.4964	0.8	-109.9
9.9951	333.239	9.9955	0.4	- 91.4
10.4968	291.467	10.4954	-1.4	- 76.3
10.8989	262.810	10.8983	-0.6	- 66.2
11.4948	227.069	11.4958	0.8	- 54.0
12.0127	201.432	12.0128	0.1	- 45.0
12.4956	181.063	12.4967	1.1	- 38.9
12.9593	164.277	12.9600	0.7	- 33.7
13.4989	147.533	13.4985	-0.4	- 28.7
13.8057	139.140	13.8047	-1.0	- 26.2
14.0484	132.976	14.0482	-0.2	- 24.4
14.5019	122.593	15.5004	-1.5	- 21.5
14.9893	112.710	14.9900	0.7	- 18.90
15.5002	103.664	15.5014	1.2	- 16.56
16.0462	95.255	16.0449	-1.3	- 14.45
16.5012	89.004	16.5014	0.2	- 12.96
16.9676	83.281	16.9673	-0.3	- 11.64
17.4980	77.430	17.5006	2.6	- 10.34
18.0112	72.451	18.0090	-2.2	- 9.27
18.4994	68.123	18.4999	0.5	- 8.38
18.9407	64.578	18.9417	1.0	- 7.68
19.5009	60.514	19.5002	-0.7	- 6.90
20.0436	56.927	20.0472	3.6	- 6.24
20.2840	56.512	20.2789	-5.1	- 5.98
20.4998	54.194	20.5037	3.9	- 5.75
21.0102	51.432	21.0056	-4.6	- 5.27
22.8236	43.136	22.826	2.4	- 3.94

$T_{acoustic\ fitted}$ are the values of temperature that would be obtained in a smooth relationship of R-T for the germanium thermometer. δT is the difference between $T_{acoustic\ fitted}$ and $T_{acoustic}$. Although the δT's show some systematic deviations, particularly at the lower temperatures, the most noteworthy point is the magnitude of the δT's from 20 to 21 kelvins. Also, the values of δT at 17.5 and 18 K are significant. One can probably consider that the values of $T_{acoustic\ fitted}$ may yield more consistent and better values of temperature than those associated with the temperature of individual isotherms but the approximately ±5 mK for δT in the vicinity of 20 kelvins is distressing. It appears to indicate that errors may exist in the acoustical isotherms. Later in this report specific causes of a possible systematic error will be discussed.

A second method of smoothing the isotherms to detect possible systematic variations was achieved by fitting the isotherm slopes to expressions of temperature that were similar to experimentally observed dependencies of the second virial coefficient. The three expressions

$$f(T) = a_1 + b_1/T + c_1/T^2$$
$$f(T) = a_2 + b_2/\sqrt{T} + c_2/T$$
$$f(T) = a_3 + b_3 \ln T + c_3/T$$

yielded residuals of the same sign (there was one exception).

Table 4

Temperatures and Slopes of the Speed of Sound Isotherms

T (K)	Slope[a]	Upper Pressure Limit (Atm)	Residual
9.4956	-14.892 (.16)	0.8	-.172
9.9951	-12.098 (.17)	1.0	.106
10.4968	-10.204 (.10)	0.8	-.276
10.9002	- 8.458 (.12)	0.9	-.204
11.4948	- 5.904 (.14)	0.8	.108
12.0127	- 4.117 (.13)	1.0	.130
12.4961	- 2.573 (.08)	0.9	.165
12.9596	- 1.238 (.09)	0.9	.164
13.4989	.149 (.09)	0.8	.117
13.8057	.952 (.04)	1.0	.157
14.0484	1.528 (.13)	0.9	.155
14.5019	2.356 (.05)	1.0	-.044
14.9893	3.540 (.10)	0.9	.110
15.5002	4.634 (.06)	1.0	.198
16.0473	5.259 (.08)	1.0	-.179
16.5012	6.158 (.21)	1.0	-.059
16.9676	6.870 (.09)	0.8	-.100
17.4980	8.178 (.09)	0.9	.404
18.0112	8.121 (.06)	0.8	-.383
18.4994	9.187 (.09)	0.9	.029
18.9407	9.888 (.06)	1.1	.170
19.5009	10.384 (.10)	1.0	-.006
20.0436	11.073 (.20)	0.9	.071
20.2840	10.850 (.19)	0.9	-.411
20.4998	11.589 (.10)	1.0	.101
21.0107	11.535 (.20)	0.6	-.472
22.8236	13.458 (.09)	1.0	-.186
27.1076	16.556 (.11)	1.0	.010
29.4130	17.832 (.09)	0.7	.082
33.9758	19.798 (.22)	0.8	.235

a) The standard deviations of the slopes are in parenthesis.

If the isotherm slopes in table 4 are smooth functions of temperature, then the values of the slopes (and residuals) at 17.5 and 18 kelvins and between 19.5 and 21 kelvins clearly indicate the presence of peculiarities. This substantially supports the suggested errors in acoustical isotherms that were noted in the germanium thermometer "smoothing" of temperatures.

The preceding discrepancies and indeterminacy have prevented us until now from replacing or up-dating the NBS P2-20 (1965) scale, and presenting a liquid hydrogen vapor pressure scale, or values of ^{4}He virial coefficients.

4. Recent Acoustical Isotherm Measurements

A systematic error has been ascertained in recent acoustical thermometer experimentation. It was observed that not all data points lay on a straight line within the apparent reproducibility of the speed of sound- pressure measurements. Efforts to determine the cause of this discrepancy were concentrated in measurements at 19 K and 9 K and the cause of the data variability appears to be related to heat flow problems within the acoustical thermometer low-temperature chamber.

In order to increase the efficiency of acquiring experimental data certain set procedures have been followed. In general, the vacuum space of the acoustical thermometer was filled with some helium gas to enhance its cooling from room temperature down to the approximate temperature of measurements. Then the helium gas was evacuated by an oil diffusion pump and vacua of 1 x 10^{-7} mm of Hg were commonly achieved and maintained during the acoustical measurements. The vacuum gauge was in the pumping line at room temperature and the pumping tube within the Dewar system was of fused quartz -it was desirable that it be of the same material that was employed in other lines (the displacement measuring tube and rod that are used in connection with the piston-displacement measurements). Customarily, heat was applied to the acoustical thermometer through a heater coil that was wound around the copper top of the low-temperature portion of the instrument. A copper radiation shield surrounded the apparatus. The instrument was brought into temperature control, as indicated by several germanium resistors that were mounted in the cylinder housing which contained the helium gas, the quartz crystal and the reflecting surface. A temperature controller supplied the required heat for the apparatus and the germanium thermometers generally indicated a temperature control and temperature differential that were within one millikelvin. In the customary measurement techniques the acoustical thermometer would be at low temperatures for weeks or even months and experimental data points would be measured in a systematic manner. That is, measurements would be taken at say 19 K, the apparatus would be permitted to cool to 18 K, and measurements would be taken 18 K and so forth. At particular times the acoustical thermometer was heated to higher temperatures, e.g., 27 K, considerable outgassing of helium gas would be observed, and the instrument's temperature would again be lowered to obtain additional measurements at the regular isotherm temperatures, e.g., 19 K. After some time it was noted that the isotherm data points which were achieved after a 27 K outgassing were slightly below the "customarily" measured isotherms. The difference appeared to be greater than the expected reproducibility of the isotherm. This is supported by the data presented in figure 1 and figure 2 for the 9 K and 19 K isotherms, respectively. It was decided that, in spite of the indications of the vacuum gauge, problems of heat flow and temperature gradients existed with the acoustical thermometer chamber.

Subsequently, the radiation shielding of the instrument was modified. The innermost shield of figure 3 was incorporated in the apparatus, a heater coil was wound around the outer radiation shield and additional germanium resistors (for monitoring and controlling the outer radiation shield temperatures) were installed. The apparatus was then operated so that sufficient heating power was applied to the outer shield to cause the outer shield temperature to be a few millikelvins warmer than the cylinder of the acoustical thermometer. After some experience had been acquired in taking measurements under these modified conditions, it was ascertained that the germanium resistors which were mounted within the acoustical thermometer walls indicated stabilities within a few tenths of a millikelvin. Also the acoustical resonance peaks were sharper and the instrument could be operated at somewhat lower helium gas pressures than had been possible previously. The vertical posts that are attached to the lower portion of the inner radiation shield were used for additional thermal anchoring of the inner germanium thermometers' current leads. The use of these additional thermal anchors does not seem to noticeably affect the thermometers' stability or the instrument's operation.

When the acoustical thermometer was operated under these new conditions of thermal control, we measured isotherm data points, ("two shields" in figure 1 and figure 2) that are in close agreement with those earlier data which were acquired after the thermometer

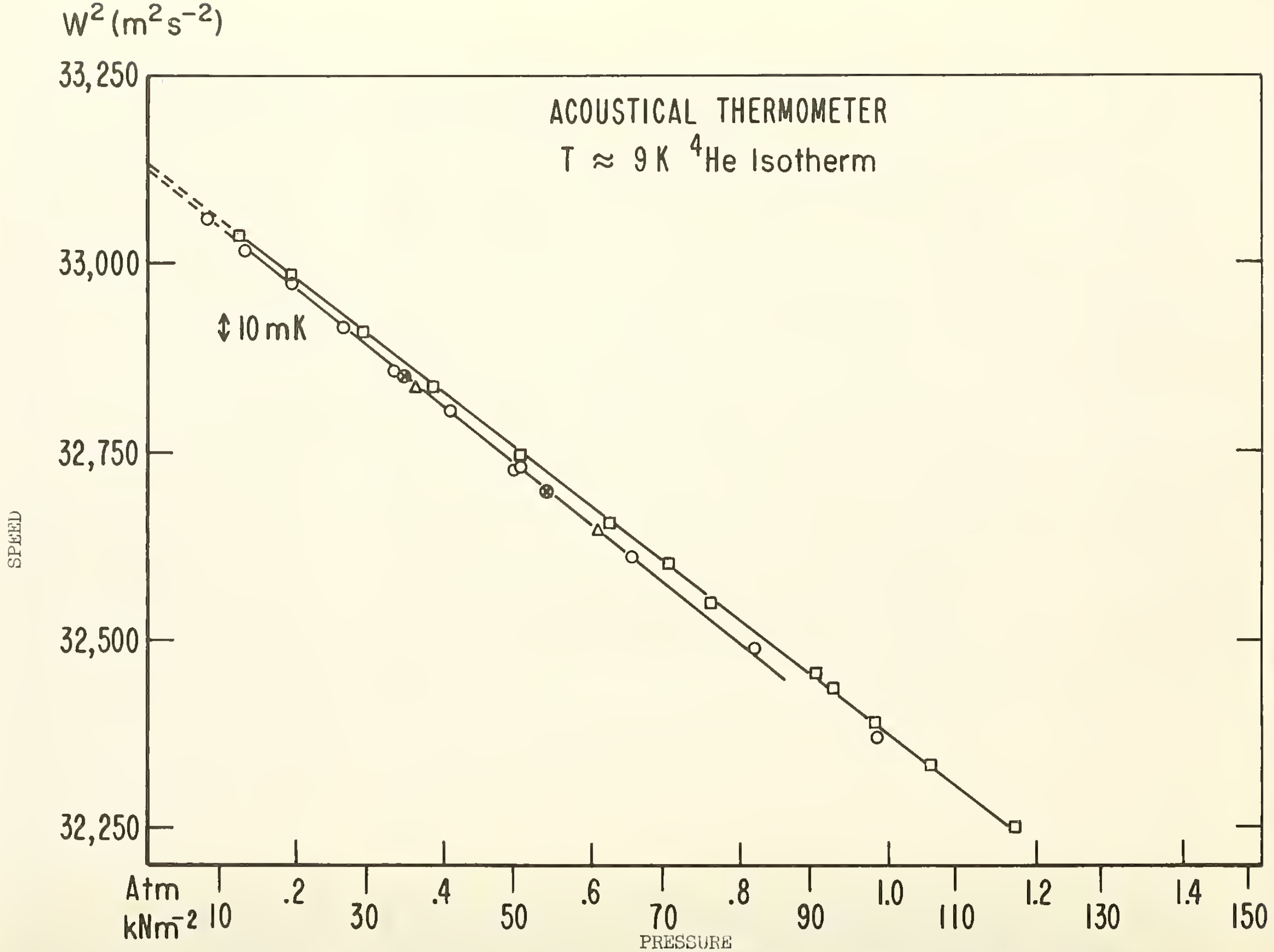


Figure 1. 8.990 K Isotherm - W^2 as a function of pressure. A comparison between data derived by different experimental procedures: preliminary measurements (single shield-not outgassed) □ 1968. Recent (1972) with two shields ○ . Recent (1972 with single shield--outgassed prior to measurements ⊗. Sonic cavity diameter doubled to investigate if H-K corrections applicable △ .

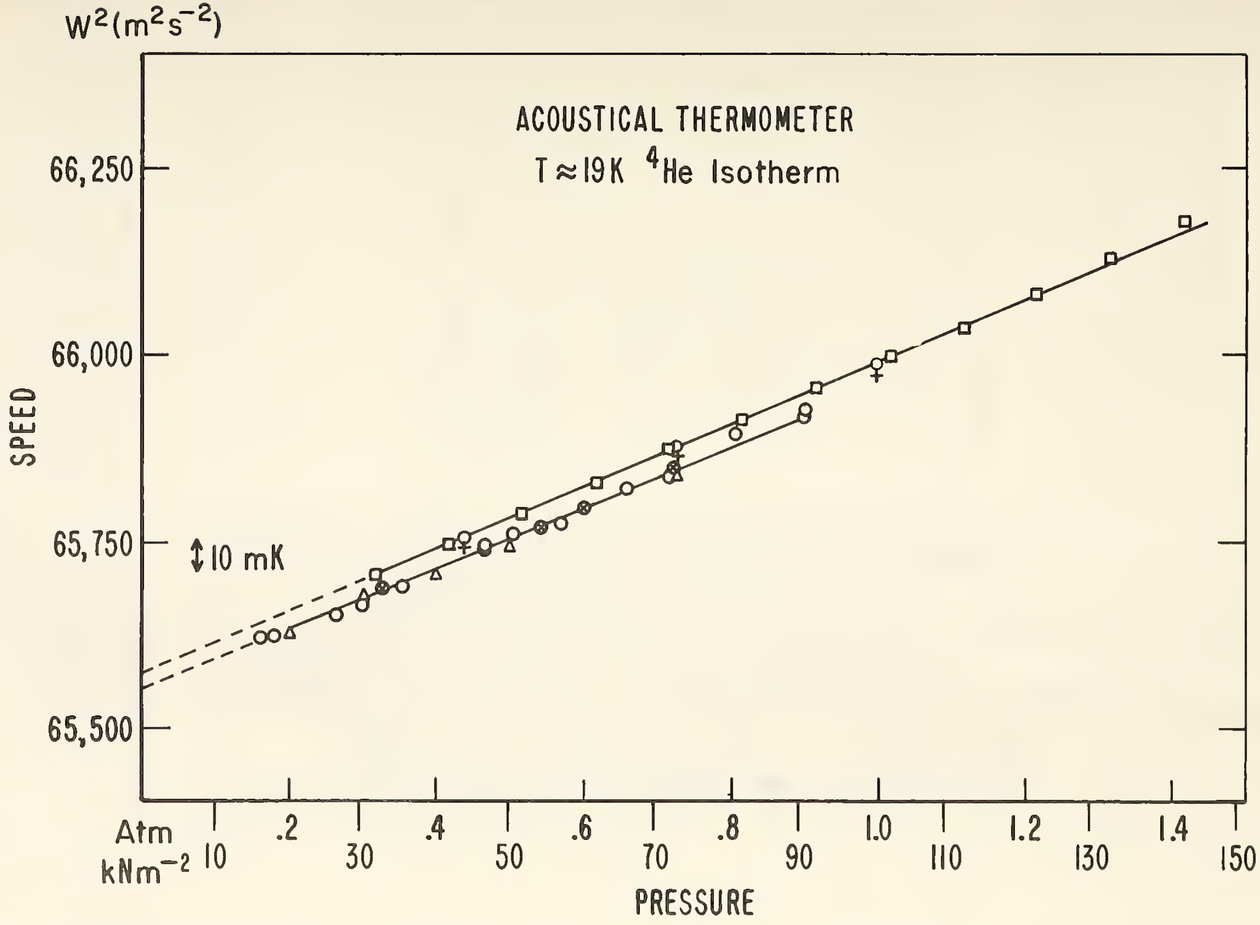


Figure 2. 18.935 K Isotherm - W^2 as a function of pressure. A comparison between data derived by different experimental procedures: preliminary measurements (single shield-not outgassed) □ 1968, ♀ 1972. Recent (1972) with two shields ○ . Recent (1972) with single shield-outgassed prior to measurements ⊗ . Sonic Cavity diameter doubled to investigate if K-H corrections applicable △ .

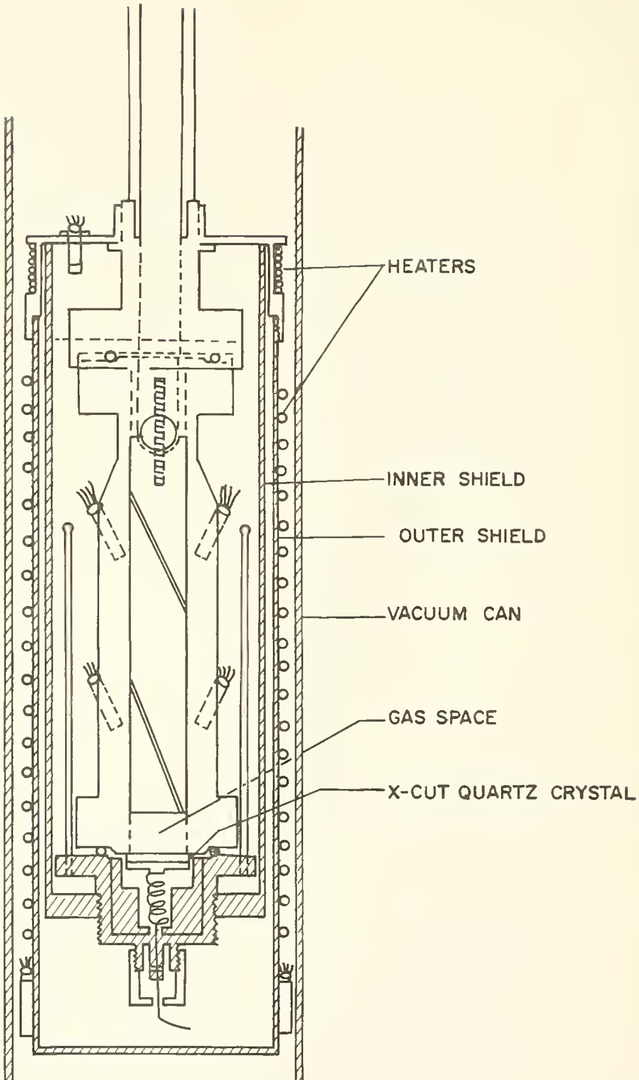

HEATERS
INNER SHIELD
OUTER SHIELD
VACUUM CAN
GAS SPACE
X-CUT QUARTZ CRYSTAL

FIGURE 3

had been outgassed at 27 kelvins. It appears that during prolonged experimentation there may be an accumulation of helium gas in the acoustical thermometer chamber. This could result from helium penetrating the fused quartz evacuation line (within the liquid helium Dewar) and its subsequent condensation, adsorption or accumulation around the lower temperature portion of the acoustical thermometer. This in turn could cause thermal gradients in the resonating helium gas and between the monitoring germanium resistors. The improved thermal stability and improved resolution of helium gas resonances which are achieved during the two shield operating conditions strongly suggest the attainment of better operational procedures. It is to be noted in figure 1 and figure 2 that this technique has resulted in isotherm determinations for 9 and 19 K which yield slightly lower temperatures and slightly different slopes than were obtained when the measurements involved the use of a single radiation shield and no special high temperature outgassing of the acoustical thermometer.

The redefinition of isotherms between 9 and 21 K has not been continued because it was desirable to eliminate another possible source of systematic error. It was mentioned earlier that the measurement of the reflecting piston's displacement is effected by measuring the displacement at room temperature of the end of a fused quartz rod which extends downward approximately one meter and is connected to the copper piston by a ball joint. The fused quartz rod, and a surrounding fused quartz tube that supports the low temperature components of the acoustical thermometer, pass through temperature gradients which exist in the liquid helium Dewar. It is possible that, despite the relatively low coefficient of expansion for fused quartz, the temperature gradients may change or the fused quartz rod does not attain adequate thermal equilibrium with its surroundings during the course of the experimental measurements. To eliminate this possible source of error it has been decided to replace the existing piston-displacement measuring system with a laser interferometer. It will essentially measure the displacement of the upper end of the reflecting piston relative to a surface in the acoustical thermometer which is maintained at low temperatures -- more specifically, a reference corner cube will be mounted on the horizontal surface, figure 3, of the component that accommodates the main heater coil. This design, in addition, to providing a more accurate displacement measurement will permit the use of a thin wall stainless steel tubing for suspending the acoustical thermometer. Fused-quartz and metal epoxy joints can be replaced by solder joints, the instrument will not be so fragile and the fused quartz evacuation line, which may have been a contributing factor to the thermal instability (described in the previous paragraphs), will be replaced by a stainless steel line. Some of the rebuilding of the acoustical thermometer, to accommodate the laser interferometer, and preliminary operational checking of the laser system have already been performed. It is also hoped that the detection of gas resonance in the acoustical thermometer can be discerned digitally -- it has been detected in the past by the visual observation of a voltmeter. These apparatus changes should lead to the elimination of possible sources of systematic error and permit the determination of better isotherms.

5. Helmholtz-Kirchhoff Equation

It was stated earlier in this report that the value of W is, of course, the phase speed corresponding to whatever mode exists in the tube of gas and it is supposed that this mode is sufficiently like the plane wave mode to allow the identification of W, for our purpose, as the free-space value.

The equations derived by Helmholtz [7] and Kirchhoff [8] are based upon the effects of viscosity and heat conduction at the boundary walls for a gas that travels along the length of a cylinder. The equations assume that the amplitude of the sound waves are uniform over the whole cross-section of the cylinder and predict that both the speed and the absorption differ from free space values. For the speed

$$W = W_o \left[1 - \frac{1}{2b} \sqrt{\frac{\eta_e}{\rho \pi f}}\right]$$

where W is the speed within a cylinder;

W_o is the free space speed

b is the radius of the tube

ρ_o is the density of the gas

f is the frequency of the sound

and η_e is an effective viscosity that is related to η, the real viscosity of a gas by

$$\eta_e = \eta [1 + \{(\gamma - 1) \sqrt{\frac{K}{C_p \eta\gamma}}\}]^2$$

γ is the ratio of specific heats

K is the thermal conductivity of the gas

and C_p is the specific heat at constant pressure.

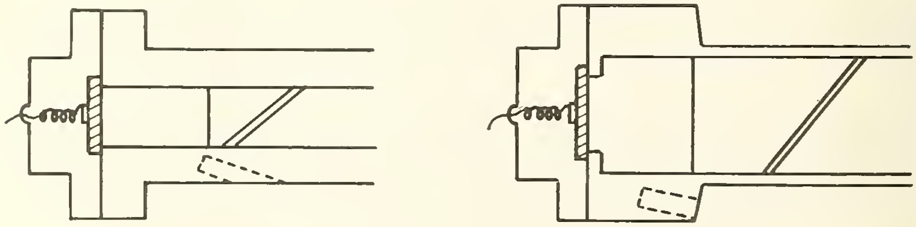
While these equations [9] have been experimentally investigated at frequencies up to 120 kHz and for tube diameters of a few millimeters, information is lacking at 1 MHz and higher. There is some verification of the equations at the relatively low frequencies but, at the very least, questions have been raised concerning the effect of the engineering finish of the boundary surface.

We thought that it would be both desirable and interesting to determine if the Helmholtz-Kirchhoff (H-K) equations were applicable to the NBS acoustical thermometer. In the correction term

$$\frac{1}{2b} \sqrt{\frac{\eta_e}{\rho \pi f}},$$

increases in both the cylinder diameter and the frequency should increase the value of the measured sound speed within the cylinder. For an acoustical isotherm of W^2 versus pressure or density there should be a noticeable bending of the isotherm with decreasing pressure. The temperature dependency of η_e is such that these effects should be greater at higher temperatures. For our acoustical thermometer b is close to 0.5 cm and it operates at 1 MHz. At an operating temperature of about 19 K, see figure 1, the H-K equations would predict that the data point at 0.25 atmospheres would depart from the isotherm linearity by the equivalent of about 8 millikelvin -- there would be a systematic decrease of W^2 from linearity as p becomes smaller. As yet, both in the plotting of isotherm data and in its analysis by computer, it has not been possible to detect systematic curvatures at low pressures.

Another experiment was conducted to check the applicability of the H-K equation for our acoustical thermometry. Another gas chamber was constructed and its principal diameter was close to 2 cm. Figure 4a indicates the usual design of the containing gas space; figure 4b shows the design of the chamber of larger diameter.



(a) (b)

FIGURE 4

We should have preferred that the entire cylindrical gas volume, to the right of the quartz crystal, in figure 4b, be of the 2 cm dimension but we desired to use the same quartz crystal that had been employed in previous experiments. One may assume that the larger diameter gas volume would cause a higher value for the measured speed of sound because the H-K correction term would be smaller; in figure 2, at 0.25 atmospheres, the measured speed of sound would be the equivalent of about 4 millikelvins higher than that which was measured with a cavity of customary design. The measured data points for the 2 cm cavity do not indicate that this is the case in figure 1 and figure 2.

As an additional check on the applicability of the H-K equations for our measurements it is highly desirable that the acoustical thermometer be operated at higher frequencies. While it was not convenient to do this during the past investigations of the H-K equations, it must and will be done when the new instrument that is being developed is finished. Additionally, if the new thermometer can be operated at yet lower pressures, it will yield greater sensitivity for detecting a possible low pressure curvature of the isotherms.

6. Calibration of Germanium Thermometers

Since 1965 the National Bureau of Standards has provided a calibration service for germanium thermometers on the NBS P2-20 (1965) scale for the general public on a reimbursable fee basis. Since the major cost associated with the calibration facility was for personnel, it was considered advantageous to increase the number of thermometers that could be calibrated during a calibration run, in order to reduce the unit cost per thermometer. Within the first calibration apparatus [3], the total number of germanium thermometers that could be accommodated was limited to four and two of the thermometers were calibration reference standards. Therefore, it was decided to construct a calibrator that could accommodate at least six thermometers and to update the existing support equipment.

Below will be discussed the improvements that have been incorporated in the new calibration apparatus and the stability of the two reference germanium thermometer standards over the last seven years. These two resistors are of a group of six that maintain the NBS P2-20 (1965) temperature scale.

For the new apparatus a vacuum seal, fabricated from stycast resin, was employed to admit electric lead lines into the evacuated chamber of the calibrator. Twice the necessary number were cast within the seal to meet possible future needs. In the former apparatus the absence of an adequate number of leads was a factor that limited the number of thermometers that could be calibrated at a time. Normally, when measurements of resistance are to be made potentiometrically, the thermometers current leads are wired in series and if one of the thermometers should become open circuited, the complete calibration would have to be terminated. To avoid the necessity of such a shut-down, individual leads were wired to the current anchors within the calibrator and terminated at one external multiple switch box; thus an open circuited germanium resistor could be by-passed and the calibration continued. A secondary radiation shield was added to the vacuum environment and was attached to the main calibrator core at its base. Another selector switch box was acquired that contained more terminals and the apparatus can now accommodate seven thermometers and with a few minor changes in the wiring, nine.

During a calibration run it is desired to attain a temperature (via resistance) that is as close as possible to the "assigned" resistance values of the calibrated germanium thermometer standards. If the values of the standards are within ±2 mK of their assigned temperature, measurements of resistance are taken for all of the thermometers within the calibrator. Since the first derivative (dR/dT) of each of the calibration standards is well defined, it is relatively simple to assign normalized values of temperature to a resistance value. Then the average of temperature of both standard thermometers at each calibration point (temperature) is assigned to each measured resistance value for the other thermometers that are to be calibrated.

Table 5

```
                                                          OMNITAB
DATE*...............                                            NO. OF RESISTORS....
SUBMITTED BY-(1) ......................(2)................. (3)..................(4)..................(5)................
 T(2-20)SCALE   T (CAL) R565   T (CAL) R540   T (CAL) AVG  |  R565 (SCALE)   R565 (CAL)   R540 (SCALE)   R540 (CAL)

    2.3240         2.3242         2.3244     |   2.3243  |  10821.0000   10818.0000   11472.0000   11467.0000
    2.8070         2.8071         2.8072     |   2.8071  |   6640.4000    6640.0000    7049.8000    7048.5000
    3.2110         3.2109         3.2113     |   3.2111  |   4818.9000    4819.1000    5122.8000    5121.7000
    4.2120         4.2120         4.2124     |   4.2122  |   2625.2000    2625.2000    2799.6000    2799.0000
    5.0240         5.0240         5.0241     |   5.0241  |   1792.3500    1792.3800    1916.8000    1916.6800
    6.0570         6.0568         6.0571     |   6.0570  |   1184.3200    1184.4200    1271.7400    1271.6700
    6.9820         6.9820         6.9823     |   6.9822  |    851.2900     851.2800     917.5200     917.4200
    8.0670         8.0666         8.0669     |   8.0667  |    595.9300     596.0100     644.9900     645.0100
    8.9910         8.9909         8.9910     |   8.9910  |    450.7500     450.7600     489.3100     489.3100
    9.8860         9.8860         9.8863     |   9.8862  |    351.5700     351.5690     382.5400     382.5090
                                             |           |
   10.9010        10.9010        10.9013     |  10.9012  |    272.1600     272.1500     296.6900     296.6680
   12.0160        12.0160        12.0154     |  12.0162  |    211.6020     211.6010     230.9520     230.9310
   12.9610        12.9610        12.9614     |  12.9612  |    174.7370     174.7370     190.7990     190.7860
   14.0480        14.0480        14.0487     |  14.0484  |    143.4480     143.4480     156.6480     156.6280
   14.9920        14.9920        14.9923     |  14.9922  |    123.0180     123.0180     134.2940     134.2870
   16.0480        16.0478        16.0481     |  16.0480  |    105.2660     105.2690     114.8490     114.8470
   16.9690        16.9688        16.9688     |  16.9688  |     92.9640      92.9660     101.3670     101.3690
   18.0090        18.0087        18.0089     |  18.0088  |     81.7310      81.7340      89.0490      89.0500
   18.9410        18.9406        18.9411     |  18.9409  |     73.4880      73.4910      80.0070      80.0060
   20.0510        20.0506        20.0510     |  20.0508  |     65.3950      65.3980      71.1300      71.1300
```

Table 5 typifies the procedure for assigning temperatures to germanium resistors that have been calibrated. The temperature in the Column T (2-20) scale are the temperatures that are associated with the values of resistance, "R565 (scale)" and "R540 (scale)", for the standard resistors 565 and 540. The values under "R565 (cal)" and "R540 (cal)" are the resistance values at which the actual calibration of unknown germanium resistors were performed. Through the respective dR/dT's, the "T (cal) R565" and "T (cal) R540" are calculated and from these "T (cal) avg" is obtained. "T (cal) avg" are the temperatures that correspond to respective resistance values for the "unknown" germanium thermometers.

When the new calibration apparatus became operational in September, 1971, resistor 561, which had been compared with 565 and 540 twice previously, was again installed to assess the maintenance of the provisional temperature scale. A comparison of the average value of the standards with resistor 561 and its previous calibration of 1967, indicated that the resistors 565 and 540 had maintained their calibration (relative resistance comparisons) to better than ±0.1 mK.

Since the initiation of the calibration service for germanium thermometers, a record has been maintained for the two reference standards (565 and 540). Their reproducibility of assigned resistance values is evaluated by the differences ($R_{540} - R_{565}$) between their observed values at each calibration point. Table 6 contains a compilation of the relative stability of the two standard thermometers and their relative reproducibilities over the last five years. The data involve 52 calibration runs and also include approximately 40 thermal cyclings of the calibrator from ambient to low temperatures. It also includes data that were taken after the installation of the monitor resistors within the new calibration apparatus since our primary concern is the retention and stability of the NBS P2-20 (1965) temperature scale.

Table 6

Statistical Review of the Two Reference Standards Within Calibration Apparatus

No. Runs 52	No. Cycles 40	Period Covered Nov 66 - Dec 71	
Temperature (K)	ΔT^a (mK)	±2σ (mK)	dR/dT(561) (Ω/mK)
2.3	1.0	.58	13.000
2.8	1.0	.56	5.800
3.2	1.0	.51	3.500
4.2	1.3	.63	1.350
5.0	0.5	.26	.770
6.0	0.5	.21	.440
7.0	0.6	.23	.290
8.0	0.5	.21	.190
9.0	0.4	.23	.130
10.0	0.6	.25	.093
11.0	0.5	.25	.065
12.0	0.6	.25	.045
13.0	0.7	.33	.035
14.0	0.8	.33	.025
15.0	0.6	.25	.019
16.0	0.9	.37	.015
17.0	0.7	.37	.012
18.0	0.8	.35	.010
18.9	0.9	.44	.008
20.0	1.0	.47	.007

a) Indicates maximum difference in "equivalent temperature" between the two reference standards ($T_{540} - T_{565}$).

Below 4.2 and above 16.0 K there appears to be a larger spread between the assigned resistance values and their realization during a calibration run, i.e., both ΔT and 2σ appear to increase at both temperature extremes. At 4.2 K and below, the normal procedure is to admit ^{4}He exchange gas to the vacuum can to hasten the cool down of the interior of the calibration apparatus and then to reduce the vapor pressure of the liquid helium bath to a pressure below the lambda point. Meanwhile the vacuum chamber is being pumped out and, when the automatically controlled bridge current approaches a steady-state current to the heater of the calibrator and the vacuum pressure remains at a steady value of 10^{-7} mm, calibration measurements are made. In the former calibration apparatus there was a time limitation in which all the resistance values could be taken because of the gradual drift upwards in the temperature of the calibrator. This could be in part due to the continuing outgassing of the calibrator. In the present apparatus, temperature controlling ata selected low temperature is possible for hours and the problem of drift seems to have been eliminated. Above 16 K the dR/dT's of the resistors become smaller and the uncertainty in the measured values of resistance is approaching our measurement capability. In our last comparison of resistance thermometer 561 with the two monitoring standards there were indications that resistance thermometer 565 may be experiencing a slight drift in its calibration at the higher temperatures (see table 6).

The new calibration apparatus has made it possible to reduce the germanium thermometer calibration costs from $1,100 to $600. This of course depends upon the receipt of enough thermometers so that at least four can be calibrated at one time.

7. Discussion

As was indicated previously in this report, the acoustical thermometry at NBS will be continued but a laser interferometer will be employed for wavelength determinations. When the final measurements have been made they may or may not lead to the revision of the temperature scale NBS P2-20 (1965). At the present time there is considerable activity concerning temperature determinations below 20 kelvins by several national laboratories. Under the auspices of the Comité Consultatif de Thermométrie a committee on thermometry below 90 kelvins has been formed and the Australian National Standards Laboratory (CSIRO) has undertaken the task of performing measurements to compare temperature scales below 20 or 30 kelvins. The NBS has calibrated three germanium thermometers, which will be sent to CSIRO, and similar contributions from PRMI, NPL, Leiden, Iowa State University and CSIRO (and, possibly, other laboratories also) are expected. NBS will submit additional acoustical thermometry data as they become available. Although our new measurements will be reported to the public, it may be advantageous to await the extension of IPTS-68, rather than have the NBS present a modificiation of NBS P2-20 (1965) for calibration purposes.

The reader's attention is called to two papers that will shortly be appearing in Metrologia. The first is a contribution from Professor C. A. Swenson, of Iowa State University: "Relationship from 1 to 34 K Between a Paramagnetic Salt Temperature Scale and Other Scales; an Addendum". The second will concern the realization of low temperature fixed points by Dr. K. H. Berry of the National Physical Laboratory.

Table 7

	$NBS_{Acoustic\ Smooth}$	$NPL_{Acoustic}$	$NPL_{P\text{-}V\ Isotherms}$
^{4}He NBP (K)	4.225 ±.001	4.2235 ±.0018	4.2240 ±.0007
e-H_2 TP (K)	13.8047 ±.001		
e-H_2 NBP (K)	20.2789 ±.005	20.2643 ±.0049	20.2746 ±.0013

It is appropriate at this point to make reference to table 7, which includes values of temperature that have recently been reported from NPL for the normal boiling points of ^{4}He and e-H_2. The "NPL acoustic" are values of temperature and their uncertainties that were obtained with the NPL low frequency acoustical thermometer [10]. The NPL p-v isotherm values were obtained by K. H. Berry and reported in the Annual Report 1971 of the Division of Quantum Metrology of the National Physical Laboratory. The "NBS acoustic smooth" values have also been cited earlier [11,12]. It should be repeated for clarity that the limits on 4.225 represent the scatter of the isotherm data points while the limits on 13.8047 and 20.2789 represent the variations in acoustically determined temperatures of the isotherms that were fitted with germanium thermometers in the vicinity of 13.8 and 20.27, respectively -- presented in table 3. Unpublished work [13] on ^{3}He p-v isotherms by Dr. R. Sherman of the Los Alamos Scientific Laboratory also indicates that the NBP of ^{4}He is about 10 mK greater than the temperature that is assigned to this fixed point on the T_{58} [14] ^{4}He vapor-pressure scale.

8. References

[1] H. H. Plumb and G. Cataland, Metrologia 2, 127 (1966).

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

[3] G. Cataland and H. H. Plumb, J. Research Natl. Bur. Standards (U.S.) 70A, 243 (1966).

[4] A van Itterbeek, *Progress Low Temp.* Phys. I, 355, North Holl. Publ. Co. 1955.

[5] L. Bergman: *Der Ultraschall*, S. 501. Stuttgart: Hirzel 1954.

[6] W. H. Keesom: *Helium*, p. 30, Amsterdam: 1942.

[7] H. Helmholtz, Verhandlungen des Naturhistorisch-medecinischen Variens zu Heidelberg 3, 16 (1863).

[8] G. Kirchhoff, Ann. Phys. Lpz., 134, 177 (1868).

[9] A. Wood, *Acoustics*, p. 251 London and Glasgow (1940).

[10] A. R. Colcough, Vol. 4, *Temperature, Its Measurement and Control in Science and Industry,* published by Instrument Society of America, Pittsburgh, Pennsylvania (In Press).

[11] G. Cataland and H. H. Plumb, J. Research Natl. Bur. Standards (U.S.) 69A, 531 (1965).

[12] G. Cataland and H. H. Plumb, Vol. 4, *Temperature, Its Measurement and Control in Science and Industry,* published by Instrument Society of America, Pittsburgh, Pennsylvania (In Press).

[13] R. Sherman - Oral report presented at the 5th Symposium on Temperature, June 21, 1971, Washington, D. C.

[14] F. G. Brickwedde, H. van Dijk, M. Durieux, J. R. Clement and J. K. Logan, J. Research, Natl. Bur. Standards 64A, 1 (1960).

☆ U.S. GOVERNMENT PRINTING OFFICE : 1973—511-325/234

FORM NBS-114A (1-71)

U.S. DEPT. OF COMM. **BIBLIOGRAPHIC DATA SHEET**	1. PUBLICATION OR REPORT NO. NBS TN-765	2. Gov't Accession No.	3. Recipient's Accession No.

4. TITLE AND SUBTITLE

Low Temperature Thermometry: Interim Report

5. Publication Date
May 1973

6. Performing Organization Code

7. AUTHOR(S)
George Cataland and Harmon H. Plumb

8. Performing Organization

9. PERFORMING ORGANIZATION NAME AND ADDRESS

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

10. Project/Task/Work Unit No.

11. Contract/Grant No.

12. Sponsoring Organization Name and Address

Same as No. 9.

13. Type of Report & Period Covered Interim
Jan. 1-Dec. 31, 1972

14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

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

Earlier acoustical thermometer 'speed of sound' isotherms are compared with recent measurements. Where systematic deviations had appeared in "smoothing" through acoustically derived temperatures via germanium thermometers, a possible solution has emerged; more precise temperature control of the acoustical thermometer is desirable and has been realized. A cursory examination of the applicability of the Helmholtz-Kirchhoff equation was made with a modified sonic chamber. Measurements with the modified instrument have shown no changes in the experimental results.

The maintenance of the NBS P2-20 (1965) scale is described. A new calibration apparatus was constructed to accommodate more germanium thermometers thus reducing the calibration cost per thermometer during a calibration run.

17. KEY WORDS (Alphabetical order, separated by semicolons) Acoustical thermometer; calibrator; germanium thermometers; heat conduction; NBS P2-20 (1965) scale; 'speed of sound' isotherms; viscosity.

18. AVAILABILITY STATEMENT

☒ UNLIMITED.

☐ FOR OFFICIAL DISTRIBUTION. DO NOT RELEASE TO NTIS.

19. SECURITY CLASS (THIS REPORT)
UNCLASSIFIED

20. SECURITY CLASS (THIS PAGE)
UNCLASSIFIED

21. NO. OF PAGES
23

22. Price
$.40 domestic postpaid
$.30 G.P.O. Bookstore

USCOMM-DC 66244-P71

NBS TECHNICAL PUBLICATIONS

PERIODICALS

JOURNAL OF RESEARCH reports National Bureau of Standards research and development in physics, mathematics, and chemistry. Comprehensive scientific papers give complete details of the work, including laboratory data, experimental procedures, and theoretical and mathematical analyses. Illustrated with photographs, drawings, and charts. Includes listings of other NBS papers as issued.

Published in two sections, available separately:

- **Physics and Chemistry (Section A)**

Papers of interest primarily to scientists working in these fields. This section covers a broad range of physical and chemical research, with major emphasis on standards of physical measurement, fundamental constants, and properties of matter. Issued six times a year. Annual subscription: Domestic, $17.00; Foreign, $21.25.

- **Mathematical Sciences (Section B)**

Studies and compilations designed mainly for the mathematician and theoretical physicist. Topics in mathematical statistics, theory of experiment design, numerical analysis, theoretical physics and chemistry, logical design and programming of computers and computer systems. Short numerical tables. Issued quarterly. Annual subscription: Domestic, $9.00; Foreign, $11.25.

TECHNICAL NEWS BULLETIN

The best single source of information concerning the Bureau's measurement, research, developmental, cooperative, and publication activities, this monthly publication is designed for the industry-oriented individual whose daily work involves intimate contact with science and technology—*for engineers, chemists, physicists, research managers, product-development managers, and company executives.* Includes listing of all NBS papers as issued. Annual subscription: Domestic, $6.50; Foreign, $8.25.

NONPERIODICALS

Applied Mathematics Series. Mathematical tables, manuals, and studies.

Building Science Series. Research results, test methods, and performance criteria of building materials, components, systems, and structures.

Handbooks. Recommended codes of engineering and industrial practice (including safety codes) developed in cooperation with interested industries, professional organizations, and regulatory bodies.

Special Publications. Proceedings of NBS conferences, bibliographies, annual reports, wall charts, pamphlets, etc.

Monographs. Major contributions to the technical literature on various subjects related to the Bureau's scientific and technical activities.

National Standard Reference Data Series. NSRDS provides quantitative data on the physical and chemical properties of materials, compiled from the world's literature and critically evaluated.

Product Standards. Provide requirements for sizes, types, quality, and methods for testing various industrial products. These standards are developed cooperatively with interested Government and industry groups and provide the basis for common understanding of product characteristics for both buyers and sellers. Their use is voluntary.

Technical Notes. This series consists of communications and reports (covering both other-agency and NBS-sponsored work) of limited or transitory interest.

Federal Information Processing Standards Publications. This series is the official publication within the Federal Government for information on standards adopted and promulgated under the Public Law 89–306, and Bureau of the Budget Circular A–86 entitled, Standardization of Data Elements and Codes in Data Systems.

Consumer Information Series. Practical information, based on NBS research and experience, covering areas of interest to the consumer. Easily understandable language and illustrations provide useful background knowledge for shopping in today's technological marketplace.

BIBLIOGRAPHIC SUBSCRIPTION SERVICES

The following current-awareness and literature-survey bibliographies are issued periodically by the Bureau:

Cryogenic Data Center Current Awareness Service (Publications and Reports of Interest in Cryogenics). A literature survey issued weekly. Annual subscription: Domestic, $20.00; foreign, $25.00.

Liquefied Natural Gas. A literature survey issued quarterly. Annual subscription: $20.00.

Superconducting Devices and Materials. A literature survey issued quarterly. Annual subscription: $20.00. Send subscription orders and remittances for the preceding bibliographic services to the U.S. Department of Commerce, National Technical Information Service, Springfield, Va. 22151.

Electromagnetic Metrology Current Awareness Service (Abstracts of Selected Articles on Measurement Techniques and Standards of Electromagnetic Quantities from D-C to Millimeter-Wave Frequencies). Issued monthly. Annual subscription: $100.00 (Special rates for multi-subscriptions). Send subscription order and remittance to the Electromagnetic Metrology Information Center, Electromagnetics Division, National Bureau of Standards, Boulder, Colo. 80302.

Order NBS publications (except Bibliographic Subscription Services) from: Superintendent of Documents, Government Printing Office, Washington, D.C. 20402.

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Washington, D.C. 20234

OFFICIAL BUSINESS

Penalty for Private Use, $300

POSTAGE AND FEES PAID
U.S. DEPARTMENT OF COMMERCE
COM-215

U.S.MAIL