

TEMPERATURE SCALES BELOW 1 KELVIN

The quest to measure temperature accurately began in ancient Greece with the invention of the thermoscope—an open, oil-in-glass device that was the forebear of the familiar, sealed, liquid-in-glass thermometer. Since that time, many new types of thermometer have been invented to serve contemporary science and commerce. The two extremes of temperature will, however, always remain out of reach of our devices. The highest temperature attained by a physical phenomenon, that of the universe at its birth, is certainly beyond our measurement capabilities, although not our ability to estimate—on the order of 10^{23} kelvin. The third law of thermodynamics forbids experiments from ever reaching the lower limit, absolute zero, although they may approach it arbitrarily closely.

Nevertheless, much of the temperature range between these two limits has been explored, and experiments continue to push ever closer to them. In carefully contained nuclear hearths, experiments on Earth attempt to mimic the conditions in the Sun's interior (10^8 K) in an effort to harness a new source of energy. At the other extreme, scientists have cooled nuclei in a metal to within 0.6 nK of absolute zero to conduct thermodynamic experiments on ordered nuclear spins.

Generally speaking, there is no physical law linking the measured quantity to temperature for thermometers used in everyday applications, and thus we must calibrate such thermometers by an absolute (primary) thermometer—that is, by one based on a fundamental physical law. Several laws have been discovered (see box 1) that have simultaneously contributed to our understanding of physical phenomena and served to define an absolute temperature scale. Thus, the law governing the gas thermometer evolved from the kinetic theory of gases developed in the 19th century, and the law for blackbody radiation ushered in quantum physics early in the 20th century.

The need to provide a common basis for precise comparisons of temperature measurements has led to the

Efforts are under way to develop a temperature scale that would reach as low as 0.001 kelvin and extend the present international scale, which is compromising many experiments conducted below 0.65 K.

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evolution of a succession of international temperature scales. The development of a new temperature scale always begins with the fundamentals: The physical laws given in box 1 are used to determine T . Because these measurements often require an experimental effort sustained over many years using a complex facility, they are usually—but not exclusively—carried out at the national standards laboratories. There the metrologists are faced with the exacting challenge of establishing a satisfactory consensus among measurements that employ these absolute thermometers. They then compare their results with those of other laboratories, either by exchanging calibrated devices that accurately represent their work or by comparing the temperature values determined for certain fixed points.

To make this information useful to a wider group, a practical scale is devised from this fundamental work. This practical scale is defined by choosing a few interpolation devices, or “defining instruments,” that are to be calibrated at a number of fixed temperature points. Needless to say, great care is taken in constructing a new temperature scale and thus only five have been developed so far—in 1887, 1927, 1948, 1968 and 1990. (See figure 1.)

The status quo: ITS-90

The most recent of these temperature scales is called the International Temperature Scale of 1990.¹ Figure 2 shows the structure of ITS-90. Four defining instruments are prescribed, three of which are calibrated at several melting and triple points whose temperature values have been assigned on the basis of the international comparisons. The procedure for their use in precise interpolation between the fixed points is also prescribed.

It is apparent from figure 2 that the lower limit of ITS-90 is 0.65 K. There are several good reasons for extending the scale below this value.

One of the strongest reasons has come from investigations of the interesting properties of liquid helium-3. Below a temperature of about 0.1 K, this substance is expected to be an ideal system with which to test the predictions of the Landau theory for interacting fermions. This theory is expressed in terms of coefficients that may be determined from experiments (see box 2). The most important of these is related to the effective mass m^* of the quasiparticles. The best way to determine m^* is through a measurement of the specific heat C_v , which, in turn, requires a very precise temperature scale. Thus, specific heat determinations, as well as many related

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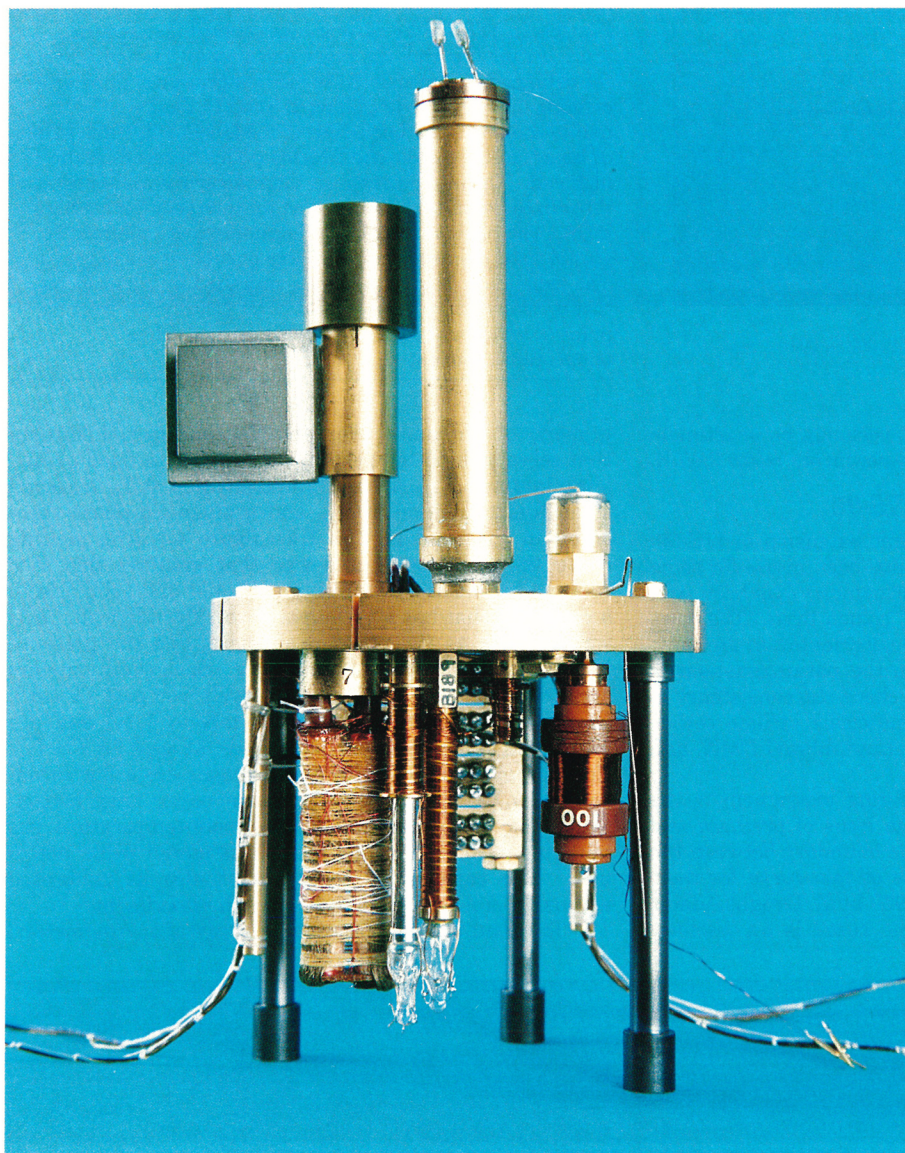


FIGURE 1. 'ROSETTA STONE' OF TEMPERATURE serves as the source of the NIST cryogenic temperature scale. Representatives of nearly all the thermometers mentioned in the text are mounted on a gold-plated copper platform. The platform is cooled to very low temperatures using a ^3He - ^4He dilution refrigerator.

studies of ^3He , proceeded apace in the 1960s and 1970s, but without the benefit of an international temperature scale. Scientists at individual laboratories had no other choice but to construct their own temperature scales, and thus different scales sprang up throughout the world. This situation led to inconsistencies. For example, discrepancies as large as 40% were found in the measured values of the specific heat of liquid ^3He in the 10–40 mK range, yielding a concomitant variation in m^* . It was commonly believed that inaccuracies in the temperature scales caused the observed discrepancies. Given the pivotal role played by m^* in the Landau theory, the resolution of this controversy through the use of an improved temperature scale was considered exceedingly important.

Liquid ^3He held an even greater secret. In 1972, it was found² to enter several new phases below a temperature of about 2.6 mK, which was labeled T_A . They eventually proved to be manifestations of the long-sought superfluidity and, indeed, last year's Nobel Prize in Physics went to discoverers David Lee, Douglas Osheroff and Robert Richardson. (See PHYSICS TODAY, December 1996, page 17.) Study of these new and very complex phases gave the low-temperature community new vigor and

stimulated a renaissance in low-temperature research in the 1970s and 1980s. The experiments were eventually accompanied by theoretical explanations, which used the normal state of ^3He as the starting point from which to derive properties of the superfluid state. Thus, many of the parameters of the Landau theory for the normal liquid reappear in expressions for properties of the superfluid (the superfluid density and susceptibility, for example, as detailed in box 2), further stressing the importance of accurately determining the normal-state properties. Moreover, the absence of a temperature scale for the region below 2.6 mK led many workers to use the expedient of reporting their results in terms of T/T_A , reasoning that their results could then be placed on an absolute basis when an accurate temperature scale became available. This situation once again called for the establishment of a common temperature scale.

Understanding the properties of liquid ^3He is not the only reason for the development of a low-temperature scale. The advent of the ^3He - ^4He dilution refrigerator has made experiments in the region from 10 mK to 1 K commonplace. However, the absence of a convenient temperature scale heightens the frustration of users who want to measure the temperature accurately. A number of adiabatic demagnetization refrigerators have also been built throughout the world, plunging experiments still deeper into the cryogenic range (μK and nK), and further extending the *terra incognita* of temperature.

A final reason for an effort to define a temperature scale in this region comes from the metrologist's desire to test physical laws over a much greater range. The outcome of

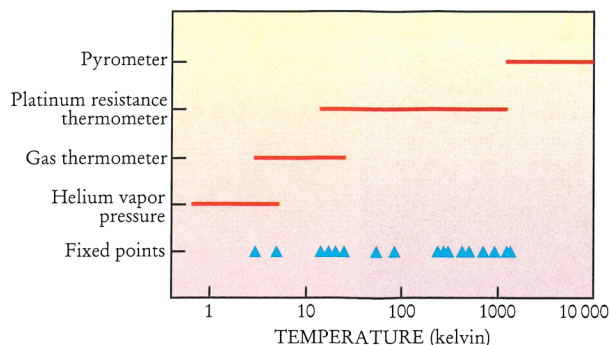


FIGURE 2. ITS-90, the current international temperature scale. At the low end, the vapor pressures of ^3He and ^4He are the defining instruments. At higher temperatures, three other defining instruments are calibrated using 17 fixed points—boiling and triple points at the lower end, triple points of liquids in the middle and freezing points of metals at the high end. The interpolating gas thermometer is calibrated at three fixed points and may be used for interpolation between them. The platinum resistance thermometer is calibrated at several fixed points and spans a large portion of the range. The radiation from a blackbody is measured by a pyrometer that is calibrated by a single fixed point (usually the freezing point of silver or gold); equation 1 is used to define temperatures above it.

this important challenge will most certainly be of ultimate benefit to others conducting their experiments below 0.65 K.

A cryogenic extension of ITS-90

Figure 3 shows a possible cryogenic extension of ITS-90. All the ingredients for the scale have been in use for some time, and their suitability for thermometry has been well tested.³ The determination of T comes first: The laws governing thermal noise and nuclear orientation are most appropriate for this region, while the paramagnetism of several materials may be used to check the consistency of the scale so developed. These materials include cerous magnesium nitrate (CMN), lanthanum-diluted CMN, and platinum.

The best candidate for a defining instrument is the melting curve of ^3He , which is the locus of pressure and temperature points that define the boundary between the liquid and solid phases. The use of this curve for thermometry was first suggested in 1967 by E. Dwight Adams of the University of Florida. The curve is an intrinsic

property of ^3He , and it even provides four special features that serve as both temperature and pressure fixed points: a minimum at $T_{\min}$, a superfluid transition at T_A , a second superfluid transition at T_{AB} and a magnetic phase transition in the solid at T_N . (See figure 4.) The melting curve thermometer is a device that employs this P - T relation by enclosing a mixture of liquid and solid ^3He in a container that has one comparatively flexible wall. This wall distorts as the pressure changes, and the pressure is sensed as a change in capacitance. Such thermometers are extremely sensitive, are relatively compact (1 cm^3), have a wide dynamic range (0.1 mK to 1 K) and are insensitive to moderate magnetic fields (at least for $T > T_N$). Counterpoised against these advantages are a few inconveniences. The melting-curve thermometer must be connected by a capillary tube to a room-temperature gas handling system in which the ^3He is stored while not in use. The capacitance sensor must also be calibrated against a pressure standard for each experiment.

To round out this formidable array of thermometers,

Box 1. Fundamental Laws for Thermometry

Each of equations 1–4 below unambiguously relates a measured quantity to temperature T . They are absolute in the sense that they contain only fundamental constants; their universality is not compromised by the introduction of sample-dependent parameters or any other constants that depend on any particular experiment.

For the radiation emitted from a blackbody, the measured quantity is the radiant energy flux $I(\nu, T)$ crossing a unit area per second at a frequency ν .

For a gas, it is the pressure P at constant density, n/V . Departures from the ideal gas law, $P = (n/V)N_0 kT$, become serious at higher densities; B and C are the temperature-dependent virial coefficients that account for the deviation.

A resistance R will exhibit inherent voltage noise whose spectral power density $S(\nu, T)$ may be measured.

The angular distribution $W(\theta, T)$ of gamma rays emitted from an oriented ensemble of radioactive nuclei (for example, ^{60}Co) may be used to measure temperature. This can be done once all the details of the decay scheme—for example, the energy level splitting Δ_{hf} —have been determined by other measurements.

The fifth equation given below relates the magnetic susceptibility χ for many paramagnetic materials (containing either nuclear or electronic spins) to temperature but introduces measurement-circuit parameters A and B , as well as material-dependent parameters θ , Δ and δ . Thus, although the function $\chi(T)$ is not known *a priori*, once the parameters in the equation are calibrated by one of the other physical laws, this function

may be used for precise interpolation and even extrapolation. When θ and δ may be neglected, the equation is known as the Curie-Weiss law.

Blackbody radiation:

$$I(\nu, T) = \frac{2\pi h \nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1} \quad (1)$$

Gas:

$$P = \frac{nN_0 k T}{V} \left[1 + B(T) \left(\frac{n}{V} \right) + C(T) \left(\frac{n}{V} \right)^2 + \dots \right] \quad (2)$$

Noise:

$$S(\nu, T) = 4RkT \quad (3)$$

Nuclear orientation:

$$W(\theta, T) = 1 + \sum_{k=1}^{\infty} B_k(T) R_k P_k(\cos \theta), \quad (4)$$

where $B_k(T) \sim \exp(\Delta_{\text{hf}}/kT)$

Paramagnet:

$$\chi = \frac{A}{(T + \Delta + \theta/T + \delta/T^2 + \dots)} + B \quad (5)$$

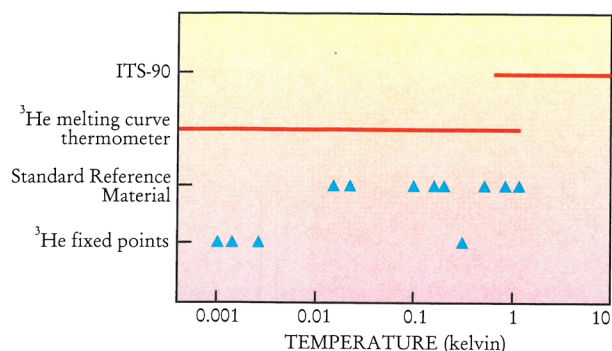


FIGURE 3. POSSIBLE CRYOGENIC EXTENSION OF ITS-90. Four fixed points are defined by features of the ^3He melting curve, and another eight are provided by the superconductive transition temperatures of materials incorporated into SRM 767 and 768. A single defining instrument, the ^3He melting curve thermometer, extends below 1 mK at the lower end and overlaps with ITS-90 at the upper end.

two fixed-point devices, which have proved to be of considerable help in this region, have also been included in the cryogenic extension scheme. NBS Standard Reference Material (SRM) 767 and 768 are devices that each contain five samples of superconducting materials.⁴ Each sample possesses a precise and reproducible transition temperature that is easily measured with an AC susceptibility bridge. Not all of the materials in the SRM devices are pure, however, and thus each device must be calibrated. Furthermore, the SRM devices are quite sensitive to magnetic fields and therefore require shielding. Nevertheless, the SRM devices have provided the means for very precise comparison of temperature scales in regions not covered by the fixed points on the ^3He melting curve.

Toward a new cryogenic temperature scale

Experiments based on absolute thermometry below 1 K were initiated in the late 1970s at the National Institute of Standards and Technology (formerly the National Bureau of Standards) in the US and at the Physikalisch-Technische Bundesanstalt (PTB) in Germany. Measurements at NIST were conducted with a noise thermometer from 6.5 mK up to and overlapping ITS-90, and with a cobalt-60 nuclear orientation thermometer in the 7–22 mK region. Direct comparison of these two absolute thermometers yielded agreement to the 0.3% level and, indeed, this cryogenic temperature scale is believed to be accurate to this level over its entire range.⁵ This scale was originally made available to other laboratories by way of the SRM 768 device and, subsequently, by way of the ^3He P - T relation.

In the early 1980s, Dennis Greywall at AT&T Bell Laboratories carefully measured the specific heat of ^3He at temperatures below 1 K for reasons mentioned above. To develop the requisite temperature scale, he replicated

Box 2. Theoretical Description of Liquid Helium-3

Consider first the normal state of liquid ^3He . Lev Landau asserted that the problem of describing the low-temperature behavior of a system of strongly interacting fermions may be reexpressed in terms of a system of weakly interacting, long-lived excitations—quasiparticles. The momentum $\mathbf{p}$ and distribution $n(\mathbf{p})$ for the quasiparticles are the same as those for an ideal (noninteracting) Fermi gas that obeys Fermi-Dirac statistics, but their energy and effective mass m^* are quite different. Indeed, m^* for ^3He quasiparticles is roughly three times that of a bare ^3He atom, indicating that an individual ^3He atom is heavily “dressed” by its interaction with the other atoms; yet the dressed quasiparticles may be thought of as weakly interacting. Landau’s phenomenological expression for the energy of the quasiparticles is

$$E = \sum_{\mathbf{p}} \varepsilon(\mathbf{p}) dn(\mathbf{p}) + \frac{1}{2} \sum_{\mathbf{p}, \mathbf{p}'} \left[f(\mathbf{p}, \mathbf{p}') dn(\mathbf{p}) dn(\mathbf{p}') + \xi(\mathbf{p}, \mathbf{p}') \boldsymbol{\sigma}(\mathbf{p}) \cdot \boldsymbol{\sigma}(\mathbf{p}') \right].$$

Here dn is the change in the Fermi-Dirac distribution of the quasiparticles from the average value at $T=0$; $f(\mathbf{p}, \mathbf{p}')$ represents the forward scattering amplitude of two quasiparticles with momenta $\mathbf{p}$ and $\mathbf{p}'$; and $\xi(\mathbf{p}, \mathbf{p}')$ represents the part of the interaction that depends on their spins $\boldsymbol{\sigma}$. For isotropic liquid ^3He the interaction will depend only on the angle θ between $\mathbf{p}$ and $\mathbf{p}'$, and may be expanded in terms of Legendre polynomials $P_l(\cos \theta)$:

$$\frac{dn}{d\varepsilon} f(\mathbf{p}, \mathbf{p}') = \sum_l F_l P_l(\cos \theta)$$

$$\frac{dn}{d\varepsilon} \xi(\mathbf{p}, \mathbf{p}') = \sum_l Z_l P_l(\cos \theta).$$

Here $dn/d\varepsilon$ is the density of states. The coefficients F_l and Z_l are related to physical parameters and thus may be determined from experiments. For instance, the specific heat C_v is related to F_1 , m^* and the specific heat of a Fermi-Dirac gas, C_{FD} , by

$$C_v = \left(\frac{m^*}{m} \right) C_{FD} = \left(1 + \frac{1}{3} F_1 \right) C_{FD} = \left(1 + \frac{1}{3} F_1 \right) \frac{\pi^2 N k^2}{2 \varepsilon_F} T.$$

Thus an important prediction of this theory is that the specific heat of ^3He should be linear in temperature. Other predictions relate F_0 and Z_0 to the speed of sound v_0 and the normal-state susceptibility χ_n , respectively:

$$v_0^2 = \frac{\bar{p}_F^2}{3 m m^*} (1 + F_0)$$

$$\frac{\chi_n}{\chi_{FD}} = \left(\frac{m^*}{m} \right) (1 + Z_0/4)^{-1}.$$

Note that the effective mass m^* appears in all the expressions.

Many properties of the superfluid state of ^3He may be related to the parameters developed for the normal state. By way of illustration, the superfluid density ρ_s and the superfluid susceptibility χ_s are given by

$$\frac{\rho_s(T/T_c)}{\rho_n} = (1 + F_1/3)^{-1} Y'(T/T_c)$$

$$\frac{\chi_s}{\chi_n} = (1 + Z_0/4)^{-1} Y'(T/T_c),$$

where $Y'(T/T_c)$ is a known function of temperature.

FIGURE 4. MELTING-CURVE THERMOMETRY.

- a:** Melting-curve thermometer. The chamber containing the two phases of ^3He has a flexible wall (diaphragm) that distorts when the melting pressure changes as a result of a change in temperature. This distortion is registered as a change in capacitance between the diaphragm and a fixed electrode.
- b:** The melting curve of ^3He . The nonlinear relation between the melting pressure and temperature, which separates the liquid and solid phases of ^3He , must first be established by carefully measuring both the pressure and temperature. This established relationship is then used to convert a measured pressure to a corresponding temperature.

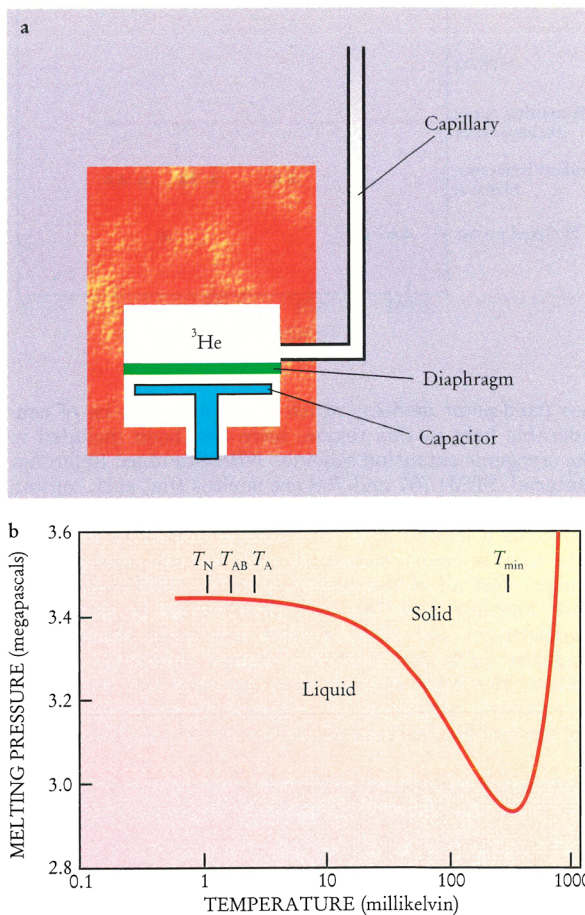
the NIST scale by calibrating a CMN thermometer from 15 to 204 mK with an SRM 768 device. In addition, because of the desirability of measuring the specific heat down to about 1 mK, Greywall devised a method to extend the scale to much lower temperatures. He did this by first measuring the low-pressure specific heat in the normal-Fermi-liquid region on a provisional paramagnetic-salt scale extrapolated from higher temperatures. Analysis of the data indicated that the temperature dependence of the specific heat was not linear as predicted by the Landau theory, and so Greywall adjusted the provisional scale in such a way that he obtained the expected temperature dependence. He correlated temperature measurements on this scale with ^3He melting pressure measurements to develop a P - T relation covering the 1 to 250 mK region. Thus, the Greywall scale, which has been used in many laboratories since 1986 as a *de facto* standard, is a hybrid of the NIST scale above 15 mK and a scale based on the assumed temperature dependence of the specific heat of ^3He below that temperature.⁶

Norman E. Phillips of Lawrence Berkeley National Laboratory has pointed out to us that the linearity of the specific heat of ^3He on the Greywall scale does not prove that the scale is accurate. Briefly, consider a temperature scale t that differs from the thermodynamic scale T in a way defined by the function $\delta = (T - t)/t$. It is simple to show that the effect of a temperature scale error on a linear specific heat is given by

$$\frac{C_T/T}{C_t/t} \approx 1 - 2\delta - t\delta',$$

where $\delta' = d\delta/dt$ and C_T and C_t are the specific heats measured on the thermodynamic and deviant temperature scales, respectively. In the case considered above, we employ the boundary condition $t = T$ above 15 mK and consider the effect of a potential scale error at lower temperatures. Below 15 mK, if δ becomes positive, then δ' must be negative, or, if δ becomes negative, δ' must be positive. In either case, the two correction terms tend to cancel and we see that the heat capacity test of temperature scale accuracy is a weak one. Indeed, if $\delta = a/T^2$, where a is any constant, then the two correction terms cancel exactly and the specific heat will be the same on both scales.

Due to the fact that the NIST scale did not extend below 7 mK, Adams and his coworkers used ^{60}Co nuclear orientation and platinum NMR thermometry to devise a scale covering the 0.5 to 25 mK region.⁷ After adjusting their ^3He melting pressure scale to coincide with the NIST value at $P_{\min}$, they found that their temperature measurements agreed with those of NIST in the region of overlap to within about 0.3%. By using NIST data from 25 to 250 mK, a P - T equation for ^3He was developed spanning the 0.5 to 250 mK range. Near 1 mK, this scale is believed to be accurate to 1%.



Last year, Gerhard Schuster and his coworkers at PTB published⁸ a comprehensive P - T relation for ^3He covering the range from 1 mK to 1 K. This scale has its origins in the ITS-90 range above 1 K, where a CMN thermometer was calibrated; the resulting equation was then extrapolated down to about 40 mK, where poor thermal equilibration of the salt prevented further extrapolation. The CMN thermometer was then used to calibrate a platinum NMR thermometer whose Curie-law relation was extrapolated down to 1 mK. Noise thermometry was used in both the CMN and platinum thermometry ranges to check for thermodynamic consistency. The PTB group estimates that the scale has an inaccuracy of about 0.1% at 50 mK, increasing to about 1% at 1 mK.

Scales in the balance

To compare the temperature scales outlined above, one must first deal with the fact that, in general, measurement errors in both temperature and pressure lurk in the various P - T relations. In this regard, the importance of the ^3He fixed points cannot be overemphasized, for, at these points, one can make *independent* measurements of both temperature and pressure and then use them to differentiate between the two types of error. Thus, to make meaningful temperature-scale comparisons, it has become common practice to adjust the pressure scales used in different laboratories to align them as nearly as possible. In the comparisons described below, the ^3He pressure scales have been normalized at $P_{\min}$ because this fixed point is most easily realized and, as shown in the table on page 41, recent values for $P_{\min}$ obtained by workers at

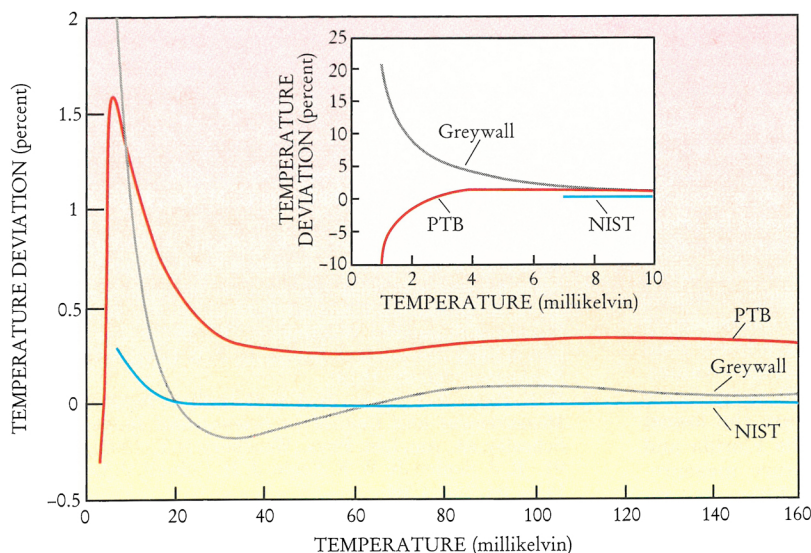


FIGURE 5. COMPARISON OF DISCREPANCIES $(T_{UF}-T_x)/T_{UF}$ (in percent) between three temperature scales using the University of Florida temperature scale as the reference.

NIST, at PTB and by Johan Bremer and Marten Durieux at the Kamerlingh-Onnes Laboratory in The Netherlands⁹ are in agreement to within the ± 50 -pascal capability of current pressure metrology. (This result is significant in its own right for it demonstrates that, if sufficient care is exercised, virtually identical pressure scales can be realized on an independent basis.)

In figure 5, the various temperature scales are compared against one another using the University of Florida P - T relation as a common reference function. The figure does not extend to temperatures that overlap the ITS-90, because the Greywall and Florida equations do not extend above 250 mK and the NIST/PTB comparison is unchanged above that point. Above 25 mK, the NIST and Florida scales are identical, and so the deviations are, of course, zero. In the 7 to 25 mK region, the NIST and Florida temperature scales agree to within about 0.3%. This is a notable result indicating that absolute thermometers, developed and operated independently, and compared by way of ^3He melting pressure measurements, can yield results that agree to within the estimated experimental error.

The Greywall scale agrees well with the NIST scale in the region above 15 mK, although the required adjustment of the ^3He pressure scale at $P_{\min}$ is rather large. This agreement indicates that the SRM 768 fixed points successfully transferred the NIST scale to Greywall's labo-

ratory. Below 15 mK, Greywall temperatures are progressively lower than corresponding values on both the NIST and Florida scales, the difference mushrooming to about 20% at 1 mK. Examination of the table below, however, indicates that Greywall and Florida report temperatures for the three low-temperature fixed points that are in agreement at the 1% level. The resolution of this paradox is found in the table, where we see that Greywall's value for the difference $P_A - P_{\min}$ is far lower than that reported by the other laboratories. This means that Greywall's P - T relation lies beneath the Florida relation and, consequently, temperatures calculated from the Greywall equation will be lower than those derived from the Florida equation, as indicated in figure 5. Of course, one can renormalize the Greywall pressure scale at one of the low-temperature fixed points, and, indeed, the PTB group did that recently.¹⁰ Although this adjustment greatly reduces temperature differences in the superfluid region, it destroys the excellent agreement mentioned above for temperatures above 15 mK, the very region in which the Greywall scale was created. It also exacerbates the discrepancy in $P_{\min}$ values between Greywall and NIST. Thus, although temperatures on the Greywall scale agree well with the Florida values at the low-temperature fixed points and with the NIST scale at higher temperatures, there does not seem to be any physically plausible adjustment to the Greywall pressure scale that will allow another laboratory to gain the full benefit of the Greywall temperature scale over its entire range.

The PTB and NIST temperature scales differ by essentially a constant 0.3% from the low end of the ITS-90 down to about 40 mK. Because the melting curve's sensitivity $T(dP/dT)$ changes substantially over this interval, one would not expect this behavior if the discrepancy were associated with ^3He pressure measurements. Therefore, this result reflects real differences between the NIST noise

Helium-3 Melting-Curve Data at the Fixed Points

	$P_{\min}$ (MPa)	$P_A - P_{\min}$ (Pa)	T_N (mK)	T_{AB} (mK)	T_A (mK)
Halperin <i>et al.</i> ¹¹	2.93160 ± 0.00030	$502\,600 \pm 100$	1.100	2.179	2.752 ± 0.110
Greywall ⁶	2.93175 ± 0.00030	$502\,050 \pm 100$	0.931 ± 0.008	1.932 ± 0.015	2.491 ± 0.020
Hoffmann <i>et al.</i> ¹²	—	$502\,640 \pm 80$	—	—	—
Ni <i>et al.</i> ⁷	2.93118^*	$502\,574 \pm 100$	0.934 ± 0.009	1.948 ± 0.020	2.505 ± 0.025
Schuster <i>et al.</i> ¹⁰	2.93107 ± 0.00005	$502\,940 \pm 30$	0.880 ± 0.010	1.870 ± 0.020	2.410 ± 0.020
Colwell <i>et al.</i> ¹³	2.93118 ± 0.00005	—	—	—	—
Bremer <i>et al.</i> ⁹	2.93114 ± 0.00008	—	—	—	—

*Ni *et al.* adjusted their pressure scale at $P_{\min}$ to that of Colwell *et al.*

thermometer and the PTB CMN thermometry. Below 40 mK, the point where the PTB scale makes a transition from its CMN to its platinum NMR thermometer, PTB temperatures decrease more rapidly than both NIST and Florida temperatures, as was the case with the Greywall comparison. There the similarities end, however, for, as the table indicates, the PTB value for $P_A - P_{\min}$ is larger than that reported by any other laboratory. On a common temperature scale, the PTB melting curve would lie above those of the other laboratories, and temperatures calculated from its P - T relation would be higher than those obtained from the other P - T relations. As figure 5 makes clear, however, that is not the case. This inconsistency can be resolved only if PTB temperatures are lower than those of NIST and Florida at common pressure values. Indeed, the table demonstrates that the PTB assignments for the low-temperature ^3He fixed points are the lowest values reported to date. Although both the Florida and PTB groups estimate that their temperature measurements are accurate to the 1% level, the differences reported in the table are about 5%.

Unfinished business

As the above comparisons make clear, there are some significant loose ends in the thermometry enterprise from 0.65 K to 1 mK, especially at the low end of the range. In particular, we sorely need additional high-accuracy ^3He melting-pressure measurements at the low-temperature fixed points. Moreover, there is some question about which measurements can provide the best means for realizing these fixed points. Only when all laboratories can agree upon a single melting-pressure scale will meaningful temperature comparisons be possible down to 1 mK. Additional temperature measurements using absolute thermometers below 10 mK and, in particular, at the low-temperature fixed points

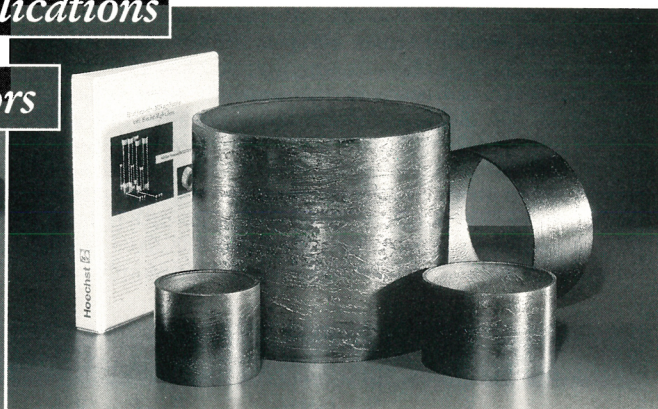
are also critical. If such experiments could be concluded successfully, it would seem likely that an official extension of ITS-90 could soon follow, to the great benefit of the low-temperature research community.

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