

Conversion of Reported Temperatures from Historical Scales to the ITS-90

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Abstract While the International Temperature Scale of 1990 (ITS-90) has been a standard for many years, there is a large amount of historical thermophysical data reported on other scales. The differences of these scales from ITS-90 is typically small, but not necessarily negligible for reference-quality work. We describe conversion to ITS-90 from 36 different scales. These include not only the relatively well-known International Temperature Scales from 1968, 1948, and 1927, but also scales that have been used for cryogenic work at temperatures below the ranges of the older international scales, including the many scales that were based on the vapor pressure of helium. Scales specific to certain laboratories are also considered. Python code has been made available for the conversions described.

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1 Introduction

The current standard scale for temperatures at and above 0.65 K is the International Temperature Scale of 1990 (ITS-90) [1]. In thermophysical property work, especially the development of correlations and the comparison of experimental data to models or theory, it is desirable to adjust reported temperatures for older data to the ITS-90 so that results and comparisons are not distorted by differences in historical scales. In many, perhaps most cases, changes in temperature scales are not significant compared to other uncertainties in the data. However, these differences can be significant for the most precise measurements. For the sake of consistency, it is good practice to convert all input data to ITS-90 when developing a thermophysical property formulation.

Some conversions are well documented, such as the conversion to ITS-90 from its immediate predecessor, the International Practical Temperature Scale of 1968 (IPTS-68). Conversions from the previous two international scales (the 1948 scale known as ITS-48 and the first such scale adopted in 1927, ITS-27) are also commonly performed. Even in these relatively simple cases, some implementations may consist of simple polynomial fits, when modern computing allows these to be performed more rigorously.

It is less appreciated that many data, especially those reported prior to IPTS-68 and those reported at liquid-helium temperatures, were reported on scales differing from the series of International Temperature Scales. In large part, this was because the international scales did not extend below the boiling point of oxygen near 90 K (ITS-27 and ITS-48) or below the triple point of hydrogen near 14 K (IPTS-68). This required other scales, most of which had no official international status, to describe temperatures below those limits. In other cases, individual laboratories maintained scales different from the international scale.

In this paper, we document methods for conversion of temperatures to ITS-90 from 36 other scales. These conversions are implemented in Python code that is available at <https://github.com/usnistgov/T90-convert>. This paper is in some ways a sequel to the 1969 paper of Hust [2], who described the differences between older scales and IPTS-68, and to the 2021 paper of Harvey [3], who provided advice about the role and usage of temperature scales in the context of thermophysical property research and correlation.

In the following, we use the standard convention of writing T for absolute temperature in kelvins and t for the temperature in degrees Celsius. Particular scales will be denoted by subscripts, often based on the year of the scale. For example, absolute temperatures on ITS-90 will be denoted by T_{90} and Celsius temperatures on ITS-48 by t_{48} .

2 Older International Temperature Scales

After the adoption of new international scales, it has been common to publish information about the difference between the new scale and its predecessor. Much of this involves comparing high-quality platinum resistance thermometers (PRTs) cal-

ibrated on both scales. These differences are approximate (at a minimum, they are at least as uncertain as the uncertainty with which the old scale could be realized), but they provide a consistent basis for conversion. These conversions can be chained together to convert older scales to ITS-90; for example, ITS-48 temperatures are first converted to IPTS-68, and thence to ITS-90.

2.1 IPTS-68

The International Practical Temperature Scale of 1968 is described in a 1969 paper [4]. An amendment to the text in 1975 did not change the temperature values on the scale [5]. While a table of differences $T_{90} - T_{68}$ was published in [1], shortly afterwards some more convenient equation representations were developed [6]. One of these had to be replaced [7] after it was established by Burns *et al.* [8] that the published table in [1] was inaccurate in the high-temperature region where IPTS-68 had been realized with type-S thermocouples.

The lowest temperature on IPTS-68 was the triple point of equilibrium hydrogen (e-H₂), fixed at $T_{68} = 13.81$ K. There is no upper limit on the scale (nor is there an upper limit for ITS-90); above 1337.58 K the scale is defined using the Planck law of blackbody radiation. Because conversion from IPTS-68 is probably the most commonly used conversion, we describe it in detail.

Equations approximating the differences $T_{90} - T_{68}$ were given by Rusby [6]. The values from $903.89 \leq T_{68}/\text{K} \leq 1337.58$ were later revised by Rusby *et al.* [7].

For the range $13.81 \leq T_{68}/\text{K} \leq 83.8$,

$$(T_{90} - T_{68})/\text{K} = \sum_{i=0}^{12} a_i \left[\frac{(T_{68}/\text{K}) - 40}{40} \right]^i, \quad (1)$$

where the coefficients a_i are given in Table 1. For $73.15 \leq T_{68}/\text{K} < 903.89$, the difference is represented by

$$(T_{90} - T_{68})/\text{K} = \sum_{i=1}^8 b_i \left[\frac{(T_{68}/\text{K}) - 273.15}{630} \right]^i, \quad (2)$$

where the coefficients b_i are given in Table 1. Equations (1) and (2) give slightly different results in their range of overlap, but the differences are smaller than the typical uncertainty of IPTS-68 measurements. Rusby recommended switching between the two formulas at a temperature of 77 K [6], and we have followed that recommendation. This switch produces a discontinuity in the conversion of approximately 0.1 mK at $T_{68} = 77$ K.

For temperatures $903.89 \leq T_{68}/\text{K} < 1337.58$, the revised equation [7] is

$$(T_{90} - T_{68})/\text{K} = \sum_{i=0}^5 c_i [(T_{90}/\text{K}) - 273.15]^i, \quad (3)$$

where the c_i are given in Table 1. The discontinuity between Eqs. (2) and (3) at $T_{68} = 903.89$ K is approximately 0.8 mK. Note that the temperature on the right side of

Table 1 Coefficients for Eqs. (1), (2), and (3)

i	a_i	b_i	c_i
0	-0.005 903		$7.868\,7209 \times 10^1$
1	0.008 174	-0.148 759	$-4.713\,599\,1 \times 10^{-1}$
2	-0.061 924	-0.267 408	$1.095\,471\,5 \times 10^{-3}$
3	-0.193 388	1.080 76	$-1.235\,7884 \times 10^{-6}$
4	1.490 793	1.269 056	$6.773\,658\,3 \times 10^{-10}$
5	1.252 347	-4.089 591	$-1.445\,808\,1 \times 10^{-13}$
6	-9.835 868	-1.871 251	
7	1.411 912	7.438 081	
8	25.277 595	-3.536 296	
9	-19.183 815		
10	-18.437 089		
11	27.000 895		
12	-8.716 324		

Eq. (3) is T_{90} , whereas the previous two equations use T_{68} . This requires iteration when converting an input temperature T_{68} , but the differences are small enough that a successive substitution scheme (using T_{68} as the initial guess for T_{90}) converges quickly. There is more inherent uncertainty in the conversion represented by Eq. (3), because this temperature range in IPTS-68 (and earlier scales) was only reproducible to about 0.2 K due to limitations of the thermocouples used to define this part of the scale.

At temperatures above $T_{68} = 1337.58$ K, the freezing temperature of gold, the temperatures on both scales are given by the Planck radiation law. Their difference is simply a function of the offset of the scales at that freezing point, where $(T_{90} - T_{68}) = -0.25$ K. The relationship given by Rusby [6] depends on the wavelength λ of the radiation,

$$(T_{90} - T_{68})/\text{K} = -0.25 \left(\frac{T_{68}}{1337.58 \text{ K}} \right)^2 \frac{1 - \exp[-c_2/(\lambda T_{68})]}{1 - \exp[-c_2/(\lambda \cdot 1337.58 \text{ K})]}, \quad (4)$$

where c_2 is the second radiation constant, taken in [6] to be 0.014 388 mK.

The wavelength dependence is only significant at very high temperatures; the wavelength-independent simplification of Eq. (4),

$$(T_{90} - T_{68})/\text{K} = -0.25 \left(\frac{T_{68}}{1337.58 \text{ K}} \right)^2, \quad (5)$$

is good to within 0.1 K up to 10000 K at typical wavelengths used for pyrometry [9]. Because such high temperatures are not relevant for this journal's audience in the thermophysical properties community, and to avoid the complication of an additional variable, our Python code uses the simplified Eq. (5). The discontinuity between Eqs. (3) and (5) at $T_{68} = 1337.58$ K is approximately 0.1 mK.

2.2 NBS-IPTS-68

Section 2.1 describes conversion from the official version of IPTS-68, which was mostly based on realizations at the National Physical Laboratory (NPL) in England. However, there was some variation in the realization of IPTS-68 at different laboratories, resulting in differences that sometimes reached several mK at temperatures below 273 K. These differences were studied thoroughly by Ward and Compton [10] via an intercomparison of capsule-type standard platinum resistance thermometers calibrated by participating National Metrology Institutes.

Here, we describe conversion from a widely used variant—the version of IPTS-68 maintained at the U.S. National Bureau of Standards (NBS). We will refer to this scale as NBS-IPTS-68. If a paper reports that their thermometer was calibrated on IPTS-68 by NBS (or calibrated in a way traceable to NBS), it would have been on NBS-IPTS-68 and conversion using only the IPTS-68 conversion equations in Sec. 2.1 would be slightly erroneous.

Ward and Compton [10] presented differences between NBS-IPTS-68 and the NPL realization of IPTS-68; the largest differences were about 4 mK near the low end of the scale (~ 13.8 K) and 3 mK near the normal boiling point of oxygen (~ 90 K). Tew [11] derived differences based on that work in the 1990s; since these have not been published we present them here in Table 2. These values are interpolated linearly to obtain $T_{\text{NBS68}} - T_{68}$ for the range $13.81 \leq T_{\text{NBS68}}/\text{K} \leq 273.15$. The difference is zero at higher temperatures. Once the NBS-IPTS-68 temperatures are converted to IPTS-68, the procedures in Sec. 2.1 are applied to convert them to ITS-90.

In principle, temperatures based on realizations of IPTS-68 from other national laboratories could be adjusted similarly based on the work of Ward and Compton [10]. For most of the laboratories included in that work, the maximum differences from the baseline IPTS-68 were roughly 2–4 mK.

2.3 ITS-48

The International Temperature Scale of 1948 (ITS-48) was described by Stimson [12]. It was defined in terms of Celsius temperatures, with 0°C at the ice point (freezing point of water in contact with air at atmospheric pressure) and 100°C at the normal boiling point of water [temperature at which the vapor pressure is 1 atm (101.325 kPa)].

The description of the scale was revised in 1960 [13] and it was renamed the International Practical Temperature Scale of 1948 (IPTS-48), but these changes did not affect the numerical temperature values. The main change relevant to this paper was adopting the triple point of water as 0.01°C (instead of the ice point at 0°C). In combination with the 1954 definition of the kelvin that defined this triple point to be 273.16 K, this meant that Celsius temperatures on the 1948 scale could be expressed as absolute temperatures (in K) by adding 273.15. Since there is no numerical difference between ITS-48 and IPTS-48, we will refer to ITS-48 throughout this work.

The lower boundary of ITS-48 was the normal boiling point of oxygen, which was fixed at -182.97°C (90.18 K). There is no upper limit to the scale.

Table 2 Table of differences for converting from NBS-IPTS-68 to IPTS-68 [11]

T_{NBS68} (K)	$T_{\text{NBS68}} - T_{68}$ (mK)
13.81	-4.0
14.006	-2.9
14.506	-1.0
15.003	-0.2
15.5035	-0.1
16.004	-0.4
16.505 15	-0.75
17.042	-1.3
17.507 15	-1.8
18.008	-2.0
18.5085	-2.3
19.009	-2.5
19.509	-2.3
20.28	-1.8
21.008	-1.0
22.007	-0.2
23.007	0.35
24.006	0.75
24.5616	1.2
25.005	1.0
26.0045	1.1
27.1041	1.2
28.005	1.2
30.006	1.1
32.008	0.9
34.008	0.6
36.007	0.4
38.006	0.2
40.006	-0.1
45.007	-0.3
50.006	-0.1
54.361	0.6
59.997	1.7
64.995	2.4
69.993	2.9
74.992	3.25
79.992	3.4
83.798	3.4
90.192	3.1
99.991	2.5
119.987	1.6
139.986	0.9
159.986	0.4
179.988	0.0
199.989	-0.1
219.991	-0.15
234.3082	-0.18
239.993	-0.2
259.997	-0.1
273.15	0.0

Conversion of ITS-48 temperatures to ITS-90 proceeds in two steps. First, the temperatures are converted to IPTS-68. Then, the IPTS-68 temperatures are converted to ITS-90 by the procedures specified in Sec. 2.1.

Conversion from ITS-48 to IPTS-68 was thoroughly described by Douglas [9]. For temperatures below 903.89 K on IPTS-68 (approximately 903.688 K on ITS-48), this can be accomplished by taking advantage of the fact that each scale is defined by equations for the ratio of the resistance of a properly constructed PRT to that at 0 °C; matching the two equations allows determining T_{48} for a given value of T_{68} , or vice-versa. Because of the variance among laboratory realizations of IPTS-68 at low temperatures mentioned in Sec. 2.2 and documented by Ward and Compton [10], there is additional uncertainty, up to a few mK, for this conversion below ~ 250 K.

The difference $t_{68} - t_{48}$ below 273.15 K is given as a function of t_{68} by Douglas's Eq. (75):

$$t_{68} - t_{48} = \frac{250.97[1 + 3.984517 \times 10^{-3}t_{68} - 5.855019 \times 10^{-7}t_{68}^2 + 4.35717 \times 10^{-12}(100 - t_{68})t_{68}^3 - W_t^*]}{1 - 2.9389 \times 10^{-4}t_{68} + 4.3741 \times 10^{-9}(75 - t_{68})t_{68}^2}, \quad (6)$$

where $W_t^*(T_{68})$ is the reference resistance function defined implicitly by a 20-term polynomial $T_{68}(W)$ in Table 2 of the definition of IPTS-68 [4].

For 273.15 K to $T_{68} = 903.89$ K ($T_{48} = 903.688$ K), the difference is given by Douglas's Eq. (80):

$$t_{68} - t_{48} = \frac{4.904 \times 10^{-7}t_{68}(t_{68} - 100)}{1 - 2.939 \times 10^{-4}t_{68}} + \varphi(t_{68}), \quad (7)$$

where

$$\varphi(t_{68}) = 0.045 \left(\frac{t_{68}}{100} \right) \left(\frac{t_{68}}{100} - 1 \right) \left(\frac{t_{68}}{419.58} - 1 \right) \left(\frac{t_{68}}{630.74} - 1 \right). \quad (8)$$

At higher temperatures up to $T_{68} = 1337.58$ K (1336.15 K on ITS-48), Douglas's Eq. (85) is used:

$$t_{68} - t_{48} = \frac{-1.3145 + 1.5016 \times 10^{-3}t_{68} + 1.5625 \times 10^{-6}t_{68}^2}{1 + 4.101 \times 10^{-4}t_{68}}. \quad (9)$$

At higher temperatures, to an upper limit of 10000 K, Douglas's Eq. (88) is used (note that it uses kelvin temperatures rather than the Celsius temperatures that appear in the previous equations in this subsection):

$$T_{68} - T_{48} = 5.56 \times 10^{-4}T_{68} + 3.84 \times 10^{-7} \left[1 - \exp \left(\frac{-22135}{T_{68}} \right) \right] T_{68}^2. \quad (10)$$

We have not implemented a conversion for temperatures above 10000 K where the wavelength must be considered; this can be done with Douglas's Eq. (87). Since all of these equations for $T_{68} - T_{48}$ or $t_{68} - t_{48}$ are expressed as functions of the 1968 temperature, successive-substitution iteration is used to compute the difference as a function of T_{48} or t_{48} .

While the lower limit of ITS-48 was 90.18 K, it was sometimes used at lower temperatures by simply extrapolating the ITS-48 PRT resistance–temperature relationship below the range in which it was derived. This extrapolated scale was called IPTS* by Lovejoy [14], who published a table of differences between this extrapolated version of ITS-48 and the NBS-55 cryogenic scale (discussed in Sec. 4.1) from $-183\text{ }^{\circ}\text{C}$ to $-222\text{ }^{\circ}\text{C}$, extending the range of ITS-48 usage to 51.15 K. For converting ITS-48 temperatures below 90.18 K, we first convert to the NBS-55 scale using cubic spline interpolation of the differences in Lovejoy’s Table 1. We then convert the NBS-55 temperatures to ITS-90 as described in Sec. 4.1.

2.4 ITS-27

The first wide-ranging standard temperature scale was the International Temperature Scale adopted in 1927 [15], now referred to as ITS-27. ITS-27 was a centigrade scale whose lower boundary was $-190\text{ }^{\circ}\text{C}$, although the lowest temperatures represented an extrapolation since the lowest calibration point was the normal boiling point of oxygen, defined to be $-182.97\text{ }^{\circ}\text{C}$ [15]. No maximum temperature was specified, but the Wien radiation formula used for high temperatures becomes increasingly inaccurate above about 4000 K.

Conversion to ITS-90 proceeds by first converting the ITS-27 temperature to ITS-48; then the ITS-48 temperature is converted to ITS-90 as described in Sec. 2.3. The conversion of ITS-27 to ITS-48 was described by Corruccini [16]. Below $630.5\text{ }^{\circ}\text{C}$ (903.65 K), the two scales are considered to be identical. Between $630.5\text{ }^{\circ}\text{C}$ and $1063\text{ }^{\circ}\text{C}$ (903.65–1336.15 K), Corruccini does not give an explicit equation for the difference, but from his paper it can be deduced that the difference is given by

$$t_{48} - t_{27} = 0.3 \frac{-226.466 + 0.5722281t - 0.0003378967t^2}{8.227 + 0.003309t}. \quad (11)$$

It is not obvious whether the Celsius temperature t in Corruccini’s formula is supposed to be on ITS-27 or ITS-48, but this choice is not significant since the difference made by the choice is negligible compared to the uncertainty (on the order of 0.1 K) of the thermocouples that were used to realize temperatures in this range. We therefore make the convenient choice of considering it to be t_{27} .

Above $1063\text{ }^{\circ}\text{C}$, Corruccini analyzed the Wien-type formula used in ITS-27 alongside the Planck-type formula used in ITS-48. His Table 2 presents Celsius temperatures on ITS-27 at values of t_{48} up to $4200\text{ }^{\circ}\text{C}$. Conversion in this range is performed by cubic spline interpolation of that table. The upper limit of this conversion is an ITS-27 temperature of $4249\text{ }^{\circ}\text{C}$, which is the highest temperature given in Corruccini’s table.

2.5 Échelle normale

In 1887, the International Committee for Weights and Measures adopted the first standard temperature scale, which was based on a hydrogen gas thermometer at the

Bureau International des Poids et Mesures (BIPM) in Paris. It was disseminated through mercury-in-glass thermometers. Its primary use was from 0–100 °C, but the calibrated thermometers could be used at somewhat lower temperatures, down to the freezing point of mercury. This scale is known as the Échelle normale (EN), sometimes rendered in English as “normal hydrogen scale” (NHS).

For the range 0–100 °C, Hall [17] compared several thermometers calibrated on the EN to PRTs measuring ITS-27 temperatures. He found that the mean differences were 5 mK or less throughout the entire range, which was smaller than the variation among thermometers carrying the EN scale. Therefore, from 0–100 °C the difference between the EN and ITS-27 can be neglected and we assume that temperatures on the EN are on ITS-27 and convert them as described in Sec. 2.4.

Below 0 °C, we observe that the freezing point of mercury was measured as -39.286 °C on the EN [18] and is -38.829 °C on ITS-90 [19]. We linearly interpolate between $t_{90} - t_{\text{EN}} = 0.457$ K at $t_{\text{EN}} = -39.286$ °C and the difference of zero at 0 °C to estimate the conversion in this range.

3 Provisional International Cryogenic Scales

Because international temperature scales prior to ITS-90 had lower limits (the normal boiling point of oxygen for ITS-27 and ITS-48; the triple point of e-H₂ for IPTS-68) that did not include temperatures of interest for cryogenics, other temperature scales were developed to fill this gap. Most of these scales had no official status; these will be described in subsequent sections. In this section, we describe two scales that were internationally adopted, known as EPT-76 and PLTS-2000, the latter of which is still a provisional standard. Two earlier cryogenic scales based on the vapor pressures of liquid ⁴He (from 1958) and ³He (from 1962) had some international status and were recommended in an appendix to the text of IPTS-68 [4]. These will be discussed in Sec. 5 along with other scales based on the vapor pressure of helium.

3.1 EPT-76

The 1976 Provisional 0.5 K to 30 K Temperature Scale is known as EPT-76 (from its name in French, Échelle Provisoire de Température de 1976 entre 0,5 et 30 K) [20]. As the name suggests, it was adopted to describe temperatures both below and somewhat above the 13.81 K lower limit of IPTS-68. At the time, it was already known that IPTS-68 deviated somewhat from the thermodynamic temperature at low temperatures, but for convenience EPT-76 was designed to smoothly join IPTS-68 at 27.1 K. “Provisional” in the name refers to the expectation that it would be superseded by a new international scale; this expectation was realized for most of its range when ITS-90 was adopted.

Based on studies with low-temperature thermometry for the development of ITS-90, a table of $T_{90} - T_{76}$ was given in the ITS-90 paper [1]. Rusby [6] gives an equation to approximate the difference, which becomes as large as 4.1 mK at 27 K,

$$(T_{90} - T_{76})/\text{K} = -5.6 \times 10^{-6} (T_{76}/\text{K})^2. \quad (12)$$

The form of this equation is such that the difference becomes negligible below 5 K. Equation (12) is only valid up to 27.1 K; above that temperature EPT-76 was defined to be equal to IPTS-68 so that conversion of EPT-76 temperatures to ITS-90 uses the IPTS-68 methods defined in Sec. 2.1. This shift in methods introduces a discontinuity of approximately 0.8 mK at $T_{76} = 27.1$ K.

3.2 PLTS-2000

Some applications require measuring temperatures below the 0.65 K lower limit of ITS-90. For this purpose, a Provisional Low Temperature Scale was adopted in 2000 based on the melting-pressure curve of ^3He ; it is known as PLTS-2000 and is described by Rusby *et al.* [21]. PLTS-2000 has a range of validity of 0.9 mK to 1 K.

For the range of overlap, from $T_{90} = 0.65$ K to $T_{2000} = 1$ K, PLTS-2000 and ITS-90 were directly compared by Pan *et al.* [22]. For conversion, we use the values of $T_{90} - T_{2000}$ as a function of T_{2000} in the "Weighted average" column of Pan's Table 2. Because there is scatter in the data, we use linear interpolation instead of a cubic spline. The differences range from approximately 1.58 mK at 0.65 K to 0.28 mK at 1 K, with the ITS-90 values being higher.

4 Older Low-Temperature Scales

Prior to the adoption of IPTS-68, no international scale was defined below the normal boiling point of oxygen near 90 K. There was, of course, much interest in lower temperatures for cryogenic work. Several laboratories developed scales based on PRTs, mostly calibrated with gas thermometers. Temperatures reported on these scales can be converted to IPTS-68 and thence to ITS-90.

4.1 NBS-39 and NBS-55

In 1939, Hoge and Brickwedde [23] at NBS developed a scale based on calibration of resistance thermometers with a helium gas thermometer; their calibration extended from the boiling point of oxygen down to the triple point of normal hydrogen (n-H_2) at 13.96 K. This scale is known as NBS-39.

It was later recognized that NBS-39 temperatures were approximately 0.01 K too high at the low end of its range, and the zero point of the Celsius scale was officially set at 273.15 K instead of the 276.16 K that Hoge and Brickwedde assumed. As a result, the NBS-55 scale was defined to be identical to the NBS-39 scale but with all temperatures reduced by 0.01 K.

NBS-55 was among the scales used to define the low-temperature portion of IPTS-68; as a result there were extensive comparisons between the two scales. Differences $T_{68} - T_{55}$ as a function of T_{68} were tabulated by Bedford *et al.* [24] in 1 K increments from 14–91 K (Bedford's Table 2). These values, along with a difference computed at the triple point of e-H_2 ($T_{68} = 13.81$ K) from Bedford's Table 1, were employed to generate a cubic spline for $T_{68} - T_{55}$. Because these difference tables

use T_{68} as the independent variable, the difference as a function of T_{55} is found by successive-substitution iteration. The resulting IPTS-68 temperatures are then converted to ITS-90 as described in Sec. 2.1.

Temperatures reported on the NBS-39 scale can be converted by subtracting 0.01 K to produce NBS-55 temperatures, and then applying the method described in the preceding paragraph.

The NBS-55 scale was sometimes extrapolated slightly below the range in which it was established, down to at least 12 K. However, we have found no comparison of NBS-55 to another scale (such as EPT-76) that would allow us to convert temperatures below 13.8135 K (the triple point of e-H₂ on NBS-55) to ITS-90. We therefore restrict our conversion to $T_{55} \geq 13.8135$ K. If it is necessary to convert lower NBS-55 or NBS-39 temperatures, a reasonable estimate would be to use the offset at the triple point of e-H₂ at $T_{90} = 13.8033$ K [1] (13.8135 K on NBS-55 and 13.8235 K on NBS-39). This offset is $T_{90} - T_{55} = -0.0102$ K and $T_{90} - T_{39} = -0.0202$ K.

4.2 PRMI-54, PSU-54, and NPL-61

Scales similar in purpose and construction to NBS-55 were developed at the Physicotechnical and Radiotechnical Measurements Institute in the USSR (PRMI-54) [25], at the Pennsylvania State University in the USA (PSU-54) [26], and the National Physical Laboratory in the UK (NPL-61) [27]. The conversion from these scales to IPTS-68 proceeds exactly as for the NBS-55 scale described above, using cubic spline interpolation of differences published by Bedford *et al.* [24] and then converting the IPTS-68 temperatures to ITS-90.

As with NBS-55, these scales were sometimes used at temperatures slightly below the triple point of e-H₂, but information for conversion only exists at and above that temperature so we restrict our conversions to that range. Once again, a constant offset equal to that at the e-H₂ triple point ($T_{90} = 13.8033$ K) may provide a reasonable guess. These offsets are $T_{90} - T_{\text{PRMI54}} = -0.0557$ K, $T_{90} - T_{\text{PSU54}} = 0.0023$ K, and $T_{90} - T_{\text{NPL61}} = -0.0096$ K.

4.3 NBS 2–20 acoustic scale

A low-temperature scale was developed at NBS in the 1960s based on acoustic thermometry in helium gas. The National Bureau of Standards Provisional Temperature Scale 2–20 was described by Plumb and Cataland [28].

Temperatures on this scale can be converted to ITS-90 by first converting them to the EPT-76 scale. This is done at temperatures from 2.3–20 K by linear interpolation of a table of differences (Table 4) published in the defining paper of EPT-76 [20]. The EPT-76 temperature is then converted to ITS-90 as described in Sec. 3.1.

Table 3 Coefficients for ITS-90 helium vapor-pressure relationships, Eq. (14)

Coef.	³ He, 0.65–3.2 K	⁴ He, 1.25–2.1768 K	⁴ He, 2.1768–5.0 K
A_0	1.053447	1.392408	3.146631
A_1	0.980106	0.527153	1.357655
A_2	0.676380	0.166756	0.413923
A_3	0.372692	0.050988	0.091159
A_4	0.151656	0.026514	0.016349
A_5	−0.002263	0.001975	0.001826
A_6	0.006596	−0.017976	−0.004325
A_7	0.088966	0.005409	−0.004973
A_8	−0.004770	0.013259	0
A_9	−0.054943	0	0
B	7.3	5.6	10.3
C	4.3	2.9	1.9

4.4 NPL-75 gas thermometry scale

A gas thermometry scale developed at NPL [29] played an important role in the development of EPT-76 and ITS-90; it is referred to as NPL-75 and covered the range from 2.6 K to 27.1 K.

Conversion of NPL-75 temperatures to ITS-90 proceeds by first converting them to EPT-76 by the equation given in [20]:

$$(T_{\text{NPL75}} - T_{76})/\text{K} = -5.6 \times 10^{-6} (T_{\text{NPL75}}/\text{K})^2. \quad (13)$$

The EPT-76 temperatures are then converted to ITS-90 as described in Sec. 3.1. The differences between ITS-90 and NPL-75 in the region of validity of NPL-75 are very close to zero, as the conversion of EPT-76 to ITS-90 via Eq. (12) almost exactly reverses the NPL-75 to EPT-76 conversion of Eq. (13).

5 Helium Vapor-pressure Scales

If the vapor pressure of a substance is known accurately as a function of temperature, its measurement can be used as a thermometer (or to calibrate another type of thermometer). This principle is used in the definition of ITS-90, which is defined by an equation for the temperature as a function of the vapor pressure of ³He from 0.65–3.2 K and two such equations for ⁴He that cover the range 1.25–5 K (one above and one below the λ -point temperature of 2.1768 K). These three equations have the form

$$T_{90}/\text{K} = A_0 + \sum_{i=1}^9 [(\ln(p/\text{Pa}) - B)/C]^i, \quad (14)$$

with coefficients given in Table 3.

The use of helium's vapor pressure as a cryogenic temperature scale dates back over a century. If the relationship between vapor pressure and temperature is well

documented for one of these older scales, the conversion to ITS-90 can be made by finding the ITS-90 temperature at which the vapor pressure (according to Eq. (14)) equals that given by the older scale. This matching of vapor pressures is more rigorous than the approach suggested in [3] that made use of tabulated differences with EPT-76 as an intermediate. In the following, we describe conversions for older helium vapor-pressure scales, beginning with two that achieved international consensus status.

5.1 1958 ^4He scale

As will be discussed below, several temperature scales based on the vapor pressure of liquid helium were developed by different laboratories beginning in the 1920s. International consensus was reached with the 1958 ^4He Scale of Temperatures, which consisted of a table relating the vapor pressure of ^4He to the temperature between 0.5 K and 5.22 K [30, 31].

Conversion of T_{58} to T_{90} is straightforward at conditions covered by the ITS-90 ^4He vapor-pressure equations, which define the scale for $1.25 \leq T_{90}/\text{K} \leq 5$. This range corresponds to $1.246806 \leq T_{58}/\text{K} \leq 4.9926976$. The vapor pressure corresponding to the input T_{58} is obtained from cubic spline interpolation of Table I in [30], and then that pressure is used to obtain T_{90} according to Eq. (14).

At lower temperatures, down to $T_{58} = 0.64710571$ K (corresponding to the ITS-90 lower limit of 0.65 K), the ITS-90 ^4He vapor-pressure equation is not valid. For this range, we take advantage of the fact that the 1962 ^3He vapor-pressure scale described below was designed to match the 1958 ^4He scale in their region of overlap. We therefore assume that these temperatures are equal to temperatures on the 1962 scale and convert them as described in Sec. 5.2. This procedure produces a small discontinuity of approximately 0.3 mK at $T_{90} = 1.25$ K.

Finally, there is a range $4.9926976 < T_{58}/\text{K} \leq 5.22$ that lies beyond the maximum of the ^4He vapor-pressure equation used in ITS-90. For these temperatures, we observe that the publication describing EPT-76 [4] showed differences between T_{58} and T_{76} becoming constant at temperatures of 4 K and above. Since EPT-76 and ITS-90 are nearly identical in this range, we apply the same value of $T_{90} - T_{58}$ obtained at $T_{58} = 4.9926976$ K (approximately 7.3024 mK) up to $T_{58} = 5.22$ K.

5.2 1962 ^3He scale

Because of the difficulty of measuring accurately the small vapor pressure of ^4He at low temperatures, the vapor pressure of the more volatile ^3He isotope (which became available in bulk quantities in the 1950s, albeit at significant expense) was developed as a thermometric reference. This resulted in the 1962 ^3He Scale of Temperatures, which extended from 0.2 K to approximately 3.324 K [32, 33]. It was designed to agree with the 1958 ^4He scale within their regions of overlap. The scale is defined by Eq. (9b) in [32], which gives the vapor pressure as a function of temperature.

For temperatures covered by the ITS-90 ^3He vapor-pressure equation, $0.65 \leq T_{90}/\text{K} \leq 3.2$, the conversion is straightforward, finding the value of T_{90} from Eq.

(14) corresponding to the vapor pressure given by the $p(T_{62})$ relationship. This range corresponds to $0.64710571 \leq T_{62}/\text{K} \leq 3.1936$.

In the small range $3.1946 < T_{62}/\text{K} \leq 3.324$ where no ITS-90 ^3He vapor-pressure equation exists, we take advantage of the fact that the 1958 and 1962 scales were constructed to agree in their region of overlap. Values of T_{62} in this range are assumed to be T_{58} and converted as described in Sec. 5.1.

5.3 Older liquid ^4He scales

The first helium vapor-pressure relationship to find significant use as a temperature scale, which we will call He24, came from the laboratory founded by Kamerlingh Onnes in Leiden, the Netherlands. The vapor pressure as a function of temperature is given up to 1.5 K by the equation on p. 23 of Verschaffelt's 1924 paper [34], while at higher temperatures it is given by the equation on the last page of the 1915 paper of Kamerlingh Onnes and Weber [35]. To convert these scales to ITS-90, the ^4He vapor pressure is simply used in Eq. (14) to calculate T_{90} .

Below the temperature that converts to $T_{90} = 1.25$ K and above $T_{90} = 5$ K, there is no ITS-90 ^4He vapor-pressure equation to match, so the temperature is first converted to the 1958 ^4He scale by matching the vapor pressures given by the He24 scale to those computed from the 1958 ^4He scale. The resulting T_{58} is then converted to T_{90} as described in Sec. 5.1. The same procedure for these outlying temperatures is applied for the He29, He32, He37, BS, He48, L55, and 55E liquid helium scales described in subsequent paragraphs; we will not repeat the description. As noted in Sec. 5.1, this produces a discontinuity of 0.3 mK at $T_{90} = 1.25$ K. Our notation for these old helium scales mostly follows that in the 1960 paper where all of these scales are compared to the 1958 ^4He scale [31].

The Leiden laboratory modified their representation of the ^4He vapor pressure (and therefore their temperature scale) several times. The He29 scale describes the vapor pressure with Eq. (6) (which is two equations, one below and one above 2.19 K) in the paper of Keesom *et al.* [36]. The He32 scale replaces the He29 scale below 2.19 K with the equation on p. 142 of the paper of Keesom [37]. The He32 scale was soon recognized [38] to have a discontinuity of about 8 mK at the boundary between equations at 2.19 K. The He37 scale results from the vapor-pressure data of Schmidt and Keesom [39]. Table IV in that paper, which ranges from 1.1 K to 4.2 K, provides differences $T_{37} - T_{32}$ separately for the regions above and below 2.19 K. The table can be extended slightly by reading a value at 1 K from Fig. 1 in [39] and a value at 4.217 K from Table I in [39]. Cubic spline interpolation was used to compute the difference, yielding T_{32} which can then be converted to T_{90} .

In 1939, Bleaney and Simon (BS) at Oxford University examined existing vapor-pressure data and used other thermodynamic information to derive a vapor-pressure equation for ^4He below the λ -point [40]. The vapor pressure is given by their Eq. (9), which contains a small quantity Δ that must be read from their Fig. 4, which we digitized and interpolated with a cubic spline. The BS scale is restricted to temperatures below the λ -point, which they stated to be 2.186 K on their scale.

The He48 scale was developed at the University of Cambridge. It was defined from 0.657 K to 5.2 K by the relationship between vapor pressure and temperature tabulated in Table I of [41]. We interpolated this table with a cubic spline to obtain $p(T_{48})$, which was then used to obtain the equivalent T_{90} .

5.4 L55 and 55E liquid helium scales

As cryogenic technology and studies of phenomena like superfluidity advanced in the 1950s, more effort was devoted to establishing an accurate temperature scale at liquid-helium temperatures. We devote a separate subsection to the L55 and 55E scales due both to their use in a number of publications and their importance in the eventual development of the internationally accepted 1958 ^4He scale described in Sec. 5.1.

The scale known as 55E was developed at the U.S. Naval Research Laboratory and is defined in [42]. The vapor pressure of ^4He was defined from 0.5 K to 5.22 K by separate equations above and below the λ -point, which was stated to be 2.1735 K on that scale. Equation (2) in [42] was used at lower temperatures and Eq. (1) above the λ -point. To obtain T_{90} , these vapor pressures are matched to the ITS-90 vapor pressure, including special procedures for $T_{90} < 1.25$ K and $T_{90} > 5$ K, just as for the 1958 ^4He scale described in Sec. 5.1.

A similar effort at the Kamerlingh Onnes Laboratory in Leiden led to the L55 scale, described by van Dijk and Durieux [43,44]. For L55, the vapor pressure of ^4He is given in tabular form from 0.9 K to 5.22 K. We applied cubic spline interpolation to the table published in [44] to derive the vapor pressure, which was then converted to ITS-90 in the same manner as for the 55E scale.

The 55E and L55 scales existed as rivals for a time, but after a series of meetings consensus was reached on a new scale that was believed to be better than either of them [30,31]. The 55E and L55 scales became obsolete with the adoption of the 1958 ^4He Scale of Temperatures (Sec. 5.1) in late 1958.

5.5 PTB-2006

Subsequent to the adoption of ITS-90, work at several institutions suggested that the ^3He vapor-pressure equation in ITS-90 deviated systematically from the thermodynamic temperature below about 1.2 K. This led to the development of a new scale known as PTB-2006; this was described by Engert *et al.* [45] and additional evidence that it more nearly matches the thermodynamic temperature was described by Fellmuth and Gaiser [46].

Conversion from PTB-2006 to ITS-90 is straightforward. The ^3He vapor pressure corresponding to T_{2006} is computed from Eq. (8) in [45]. This pressure is used to compute T_{90} according to the ITS-90 ^3He relationship in Eq. (14).

Table 4 Coefficients for converting cryogenic magnetic scale temperatures to EPT-76 with Eq. (15)

Scale	a	b	c	d	Range (K)
XAc'	0	0	0.0025	0	1.1–30
m(III)	−8.0	1.5	−0.0413	8.3	2–27
XNML	−1.5	0.41	−0.0109	0	1.1–30
MAS	−1.5	0.49	−0.0125	0	1.1–30
XPRMI	0	0.51	−0.0125	0	4.2–27
X1	0	0	0	0	0.5–3.1

6 Magnetic cryogenic scales

Another physical principle that can be used in thermometry is the temperature dependence of the magnetic susceptibility of a paramagnetic salt. This is especially useful at low temperatures, where it can cover the range of helium vapor-pressure thermometry but can also extend to higher and lower temperatures. Several laboratories developed cryogenic scales based on this principle; analysis and comparison of these scales played a large role in the development of the EPT-76 scale.

We consider the scales denoted in the EPT-76 paper [20] as $T_{\text{XAc}'}$ (from Iowa State University), $T_{\text{m(III)}}$ (Kamerlingh Onnes Laboratory, Leiden), T_{XNML} and T_{MAS} (National Measurement Laboratory, Australia), T_{XPRMI} (Physicotechnical and Radiotechnical Measurements Institute, USSR), and T_{X1} (National Physical Laboratory, England). Further information about these scales can be found in papers describing work that led to EPT-76 [47, 48] and in references therein.

Conversion of these scales to ITS-90 begins by converting them to EPT-76 as described in Table 5 of [20]. They all use the conversion equation

$$(T_i - T_{76})/\text{mK} = a + bT_i + cT_i^2 + d/T_i, \quad (15)$$

where the temperatures on the magnetic scale T_i are in K. The coefficients of Eq. (15), along with the ranges of applicability for the conversions, are given in Table 4, which is adapted from Table 5 of [20]. The EPT-76 temperatures are then converted to ITS-90 as described in Sec. 3.1.

7 Laboratory scales

Prior to the 1960s, some individual laboratories maintained their own temperature scales, whose development was seldom documented. This included laboratories that produced significant amounts of good-quality thermophysical data. As noted by Hoge [49], approximate conversion of a laboratory scale to an international scale can be performed if the laboratory reported values for established fixed points, such as the normal boiling point or triple point of oxygen.

7.1 Michels laboratory

A large amount of thermophysical property data was produced by the van der Waals Laboratory at the University of Amsterdam led by Prof. Michels.

In 1974, Bedford and Prins [50] published a careful analysis of the calibration procedures of this laboratory, based on reported fixed points, the interpolation equation used for PRTs, and knowledge of a small problem with the lab's realization of the normal boiling point of oxygen. The results are expressed in Fig. 1 of [50], which plots $t_M - t_{48}$ (where t_M is the Celsius temperature on the scale of the Michels lab) as a function of t_{48} from -190°C to 0°C . Below the normal boiling point of oxygen, these differences refer to the IPTS* scale mentioned at the end of Sec. 2.3. We digitized this graph at 1 K intervals and interpolated it with a cubic spline to convert temperatures on the Michels scale to ITS-48. The ITS-48 temperatures are then converted to ITS-90 as described in Sec. 2.3.

7.2 Giauque, PTR, KOL, and GL laboratories

Four other important laboratories that maintained their own scales were that of Prof. Giauque at the University of California, Berkeley, the Physikalisch-Technischen Reichsanstalt (PTR) in Berlin, the Kamerlingh Onnes Laboratory (KOL) in Leiden, and the Geophysical Laboratory (GL) of the Carnegie Institution in Washington. We are aware of no detailed study relating their scales to an international scale, but we can follow the approach of Hoge [49] and compare fixed points reported by those laboratories to their values on ITS-90.

Table 5 shows the data used for this procedure. At each point in the table, we computed $T_{90} - T_{\text{CAL}}$, $T_{90} - T_{\text{PTR}}$, $T_{90} - T_{\text{KOL}}$, and $T_{90} - T_{\text{GL}}$, where CAL designates Giauque's lab at the University of California. These differences were linearly interpolated to estimate the corrections of these lab scales to ITS-90. Some of the ITS-90 values in Table 5 come from fixed points used to define ITS-90 [1]; the rest come from Bedford *et al.* [19], who reported recommended temperatures on ITS-90 for a number of "secondary reference points."

Other than the entries for H_2O , the fixed-point values for the CAL scale in Table 5 come from Refs. [51] (n-H_2), [52] (O_2), [53] (N_2), and [54] (CO_2). We also use the fact that papers from Giauque's lab (in its first few decades) stated that they used a difference of 273.1 K between the Celsius and absolute scales. Since the ice point and normal boiling point of water defined 0 and 100 on the Celsius scale at the time, the absolute temperatures of those two points on Giauque's scale correspond to 273.1 K and 373.1 K. In the late 1940s, the Giauque lab began to take the ice point as 273.16 K [55], and eventually they began to use 273.15 K; this would require different adjustments at the higher temperatures on Giauque's scale. Fortunately, many of the group's papers state the value used for this point.

The non- H_2O fixed-point values for the PTR scale come from [56], except for the normal sublimation point of CO_2 [57] and the freezing point of mercury [58]. The PTR used 273.16 K for the ice point, meaning that their normal boiling point of water was 373.16 K.

Table 5 Temperatures (in K) for fixed points in ITS-90 and in the CAL, PTR, KOL, and GL laboratory scales. Blank entries mean the lab did not report that point.

Fixed point ^a	ITS-90	CAL ^b	PTR ^c	KOL ^d	GL ^e
n-H ₂ TP	13.952	13.92	13.96		
n-H ₂ BP	20.388	20.36	20.380		
Ne TP	24.5561		24.56		
Ne BP	27.097		27.073		
O ₂ ST	43.796	43.76			
O ₂ TP	54.3584	54.39	54.33		
N ₂ TP	63.151	63.14	63.14	63.150	
N ₂ BP	77.352	77.32	77.352	77.357	
O ₂ BP	90.197	90.13	90.190	90.161	
CO ₂ SP	194.686	194.67	194.689		
Hg FP	234.321		234.328		
ice point ^f	273.15	273.1	273.16	273.144	273.15
H ₂ O BP	373.124	373.1	373.16	373.144	373.15
Sn MP	505.078				505.05
Cd MP	594.219				594.05
Zn MP	692.677				692.55
S BP	717.764 ^g			717.714	717.70
Sb MP	903.778				903.15
Ag MP	1234.93				1233.35
Au MP	1337.33				1335.75
Cu MP	1357.77				1355.95
Pd MP	1828.0				1822.65
Pt MP	2041.3				2028.15

^a BP: normal boiling point at 101.325 kPa; FP: freezing point; MP: melting point; SP: normal sublimation point at 101.325 kPa; ST: solid transition between β and γ phases; TP: triple point

^b Lab of Prof. Giaque, University of California, Berkeley

^c Physikalisch-Technischen Reichsanstalt, Berlin

^d Kamerlingh Onnes Laboratory, Leiden

^e Geophysical Laboratory of the Carnegie Institution, Washington

^f Temperature at which liquid and solid H₂O are in equilibrium with atmospheric air at 101.325 kPa

^g There is an apparent typo for this value in [19]; the Celsius value in that paper is correct and is converted to kelvins here.

For the KOL scale, values for the normal boiling points of oxygen and sulfur on a centigrade scale are found in [59]. These are converted to absolute temperatures by the laboratory's value for the zero of the centigrade scale (ice point), which is 273.144 K [60], from which the normal boiling point of water on their scale follows at 373.144 K. The triple point and boiling point of nitrogen are taken from [61].

The GL scale was a Celsius scale based on nitrogen gas thermometry; its fixed points were listed by Adams [62] and further background is given by Sosman [63]. It was primarily used above 300 °C, but was defined as low as 0 °C. Despite being based on work in 1912, it was still in use as late as the 1950s [63]. We omit the values given in [62] for the freezing points of aluminum and nickel, since they do not fit well with surrounding points and are not listed as “primary” by Sosman [63]; the nickel point also has a relatively large uncertainty on ITS-90 [19]. The GL scale also used a fixed point for the melting of the mineral diopside at 1391.5 °C, but we did not find a reference-quality ITS-90 value for that quantity.

The same approach could be used for scales maintained at other laboratories, provided that values can be found for the values of some fixed points on those scales.

7.3 Other cryogenic vapor-pressure scales

On occasion, literature data are reported at temperatures that were determined based on the vapor pressure of a cryogenic fluid other than helium, such as hydrogen, oxygen, or nitrogen, with the vapor pressure of the cryogen being taken from some correlation or tabulation in the literature. In some cases the vapor pressure is used directly as the experimental temperature measurement; in other cases the vapor pressure is used to calibrate a thermometer.

In such cases, approximate conversion to ITS-90 can be performed if the source of vapor pressures is given; the approach parallels that for the helium vapor-pressure scales discussed in Sec. 5. The vapor pressure corresponding to the reported temperature is found based on the original source, and then the temperature corresponding to that vapor pressure is found based on the current reference equation of state for the fluid. Vapor pressures from state-of-the-art reference equations of state can be obtained from NIST’s REFPROP software [64].

8 Related Topics

8.1 Limits of reproducibility

While this paper has treated ITS-90 as an exact target for conversion, it should be appreciated that no two realizations of ITS-90 will be identical, due to factors such as different laboratory equipment and variation in characteristics of PRTs. There have been extensive comparisons of ITS-90 realizations at different metrology institutes, and in the temperature range 83.8–933 K (covering most thermophysical property measurements) the variance among laboratories is typically on the order of 0.5 mK, increasing to at least 1 mK at the high end of that range [65,66].

This lack of reproducibility is true of older scales as well, typically to a greater extent. As noted in Sec. 2.2, different realizations of IPTS-68 studied by Ward and Compton [10] varied by a few mK below 273.15 K.

This means that the conversions presented here should not be considered meaningful at the level of, or below, 0.1 mK, and in many cases not below 1 mK. Small

arbitrary choices for some conversions, such as whether to interpolate a table linearly or with a cubic spline, could be made differently without affecting the conversion at a physically meaningful level. It is, of course, desirable to be consistent in making conversions even if small inconsistencies would not change individual results significantly.

8.2 Thermodynamic temperature

Advances in temperature metrology since the adoption of ITS-90 have shown that the ITS-90 differs from the true thermodynamic temperature T by amounts on the order of a few mK. We do not provide any “conversion” to thermodynamic temperature because estimates of the difference $(T - T_{90})$ continue to be refined.

Those interested in the thermodynamic temperature corresponding to an ITS-90 temperature should apply consensus estimates for $(T - T_{90})$. Recent work has provided estimates of this difference, with uncertainties, below 4.2 K [46] and from 4.2 K to 335 K [67]. At higher temperatures, the most recent estimates are those in the 2011 paper of Fisher *et al.* [68]. For temperatures below 1 K, a recent evaluation of the thermodynamic accuracy of PLTS-2000 is relevant [69].

8.3 The next International Temperature Scale

ITS-90 may be replaced in the coming years by a new International Temperature Scale that would more closely approximate the thermodynamic temperature. After that point, the new scale should be used for thermophysical property research and there would be a need to convert older data to the new scale.

Undoubtedly the new scale would be accompanied or soon followed by an evaluation of its differences from ITS-90, so one could simply apply the ITS-90 conversions described here and then convert from ITS-90 to the new scale. This would be the best approach for some old scales (for example, IPTS-68 or NBS-55), but not for all of them. If the new scale is defined by the vapor pressure of helium at low temperatures, the correct approach for the helium vapor-pressure scales described in Sec. 5 would be to directly match their vapor pressures to those of the new scale, bypassing ITS-90. Similarly, for the laboratory scales discussed in Sec. 7, the best approach would be to replace the ITS-90 points in Table 5 with those on the new scale and directly interpolate corrections to the lab scales; this would require publication of recommended reference points on the new scale to replace the ITS-90 values of Bedford *et al.* [19]

8.4 Effects on heat capacity and thermal conductivity

For thermophysical quantities whose measurement involves a temperature difference, there is an additional effect of a change in temperature scale, because a ΔT on one scale will not exactly equal that on another scale. This has been discussed by Douglas [9] and by Harvey [3]. Thermal conductivity and heat capacity are the main properties for which this issue is relevant; in both cases experimental evaluation of

the property typically involves dividing by a temperature difference. It is preferable in such cases to convert the original measured upper and lower temperatures to ITS-90 and then recompute the property, but sometimes papers do not provide that detail.

For a property X where a temperature difference implicitly appears in the denominator, the value on the new scale is [9]

$$X_{\text{new}} = X_{\text{old}} \left[1 - \frac{d(T_{\text{new}} - T_{\text{old}})}{dT_{\text{new}}} \right]. \quad (16)$$

This correction is small, and in most cases negligible compared to the uncertainty of typical heat-capacity or thermal-conductivity measurements. For example, Goldberg and Weir [70] found that $d(T_{90} - T_{68})/dT_{90}$ had a magnitude below 0.04 % for temperatures between roughly 60 K and 900 K.

While in some cases (such as the conversions from IPTS-68 in Sec. 2.1) it would be possible to differentiate the conversion equation to produce analytical expressions for $\frac{d(T_{\text{new}} - T_{\text{old}})}{dT_{\text{new}}}$, we have not done so here. Those needing this derivative can compute it as a finite difference; one caveat is that the difference should not span a temperature at which the conversion method changes [for example, the $T_{68} = 903.765$ K boundary between Eqs. (2) and (3)] because there are often small discontinuities at these boundaries.

8.5 Advice for conversion

The paper of Harvey [3] offered advice related to temperature scales; we repeat a few of the more important items here. First, a conversion should not be applied based merely on the date of publication. Because it takes time for new scales to be publicized and implemented, and because publication takes time, it would be quite likely for a paper published in 1969 to have ITS-48 temperatures instead of IPTS-68. There is no substitute for reading the paper to see if the temperature scale is mentioned. If it is not mentioned, the date of submission may provide a better guess than the date of publication. For precise work, if the temperature scale used for data is not clear the extra uncertainty in temperature may need to be considered in the uncertainty budget.

Second, the range of validity of scales should be considered. For example, the ITS-48 scale had a lower limit at the boiling point of oxygen near 90 K. If a paper from 1967 reported a temperature of 50 K, we can be certain that something other than an international scale was used, and application of an ITS-48 conversion equation would produce nonsense. The Python functions we have constructed produce a `ValueError` and related message if they are invoked outside the range of validity of a scale.

In a few cases, laboratories may have developed and maintained their own scale based on gas thermometry or some other method for approximating the thermodynamic temperature. If fixed points were reported on the scale, conversion to ITS-90 as described in Sec. 7 is possible. Otherwise, if gas thermometry was used the best assumption might be to assume the scale to correspond to the thermodynamic temperature, perhaps with a small adjustment if (as was fairly common) the lab reported

the value they assumed for the zero of the Celsius scale and that zero point differed from the current value of 273.15 K.

9 Sample Conversions

While we hope people will use the provided Python code, there is value in giving sample results so that people can check the software or check their results if they wish to program conversions independently. In Tables 6 and 7, we provide the calculated differences $T_{90} - T_s$ in mK for all of the other scales discussed here. Table 6 covers lower temperatures and Table 7 higher temperatures. Scales are not listed if all of the temperatures in a table are out of their range; for example, the liquid-helium scales do not appear in the high-temperature Table 7. In both tables, the scales are listed in the order they are discussed in this paper.

Note that the entries in Tables 6 and 7 are given as a function of T_s . Differences as a function of T_{90} would be slightly different. The tabulated values are given to the nearest 0.1 μ K, but the actual uncertainties with which most of these scale differences are known (not to mention the uncertainty with which the scales can be realized) are much larger. The last few digits are meaningless in practice, but are given as aids to check programming.

10 Conclusion

Temperature scales serve a valuable purpose for ensuring the reproducibility of thermophysical property data. In many cases, the differences between historical temperature scales are negligible compared to other uncertainties in the data, and in other cases laboratories have not realized the standard temperature scale of their time with enough precision for these differences to matter. However, the most accurate data, which are typically the most important for developing recommended formulations for thermophysical properties, often are precise enough to require consideration of the temperature scale. It is therefore good practice to convert all reported temperatures to the current scale (ITS-90 as of this writing) when developing reference-quality property formulations.

We have examined 36 different scales and implemented their conversions to ITS-90, with special attention paid to the many scales that have been used at liquid-helium temperatures. In some cases, such as conversions from the previous international scales IPTS-68, ITS-48, and ITS-27, the conversion methods are fairly well established. The conversion of helium vapor-pressure scales to ITS-90 is also straightforward, at least in the ranges where they overlap with the corresponding ITS-90 equations. In other cases, the conversions are more approximate, for example involving interpolation in a published table of scale differences.

The conversions from all 36 scales to ITS-90 are implemented in Python code, which is available at <https://github.com/usnistgov/T90-convert>.

Table 6 Temperature differences $T_{90} - T_s$ in mK, where s is the scale denoted in the first column, at low temperatures. A blank entry means that the scale is not defined at that temperature. Extra digits are printed for readers to check programming; the uncertainties of these conversions and reproducibility of older scales are much larger than would be suggested by the number of digits.

Scale	$T_s = 1$ K	$T_s = 2$ K	$T_s = 4$ K	$T_s = 15$ K	$T_s = 50$ K
IPTS-68				−3.2365	−5.7193
NBS-IPTS-68				−3.0317	−5.6191
EPT-76	−0.0056	−0.0224	−0.0896	−1.2600	
PLTS-2000	0.2810				
NBS-55				−1.2295	7.3762
NBS-39				−11.2646	−2.6204
NPL-61				−0.4477	−10.3186
PRMI-54				−40.5272	−10.5236
PSU-54				13.2479	15.6591
NBS 2-20			−2.2895	−0.6601	
NPL-75			0.0000	−0.0002	
He58	3.3954	4.2282	7.0522		
He62	3.3954	4.0466			
He24	6.1752	−89.4831	16.6798		
He29	26.9441	9.8023	7.9431		
He32	26.9515	13.9135	7.9431		
He37	28.9789	−1.3217	2.5460		
BS	3.0257	−0.4542			
He48	3.0200	−1.5867	1.7807		
L55	4.8537	6.4152	4.0564		
55E	2.1042	3.6111	7.2259		
PTB-2006	0.6509	−0.0030			
XAc'		−0.0324	−0.1296	−1.8224	
m(III)		0.9928	0.4962	−7.0199	
XNML		0.7012	−0.0552	−3.4571	
MAS		0.5476	−0.3496	−4.2970	
XPRMI				−6.0967	
X1	−0.0056	−0.0224			
Giauque				31.3292	−3.6824
PTR				−5.4081	28.0187

Supplementary information

File T90.py contains the Python code for the conversions in this paper. It is possible that parts of this code could be refined in the future; the most current code will be at <https://github.com/usnistgov/T90-convert>.

Table 7 Temperature differences $T_{90} - T_s$ in mK, where s is the scale denoted in the first column, at high temperatures. A blank entry means that the scale is not defined at that temperature. Extra digits are printed for readers to check programming; the uncertainties of these conversions and reproducibility of older scales are much larger than would be suggested by the number of digits.

Scale	$T_s = 80$ K	$T_s = 200$ K	$T_s = 500$ K	$T_s = 1000$ K	$T_s = 2000$ K
IPTS-68	7.8934	12.2858	−40.4408	12.3324	−558.9339
NBS-IPTS-68	4.4930	12.3858	−40.4408	12.3324	−558.9339
ITS-48	−43.5584 ^a	45.9113	12.7862	478.2415	2093.1114
ITS-27		45.9113	12.7862	788.2362	−1894.4184
NBS-55	−1.1094				
NBS-39	−11.1124				
NPL-61	11.2976				
PRMI-54	−6.6063				
PSU-54	32.3111				
Michels		23.7685	12.7862	478.2415	2093.1114
Giauque	39.3224	18.3106			
PTR	1.4438	−3.5359			
KOL	3.4632	17.9919	5.7710		
GL			25.9325	907.2283	12081.5328

^a Extrapolation of ITS-48 known as IPTS*; see Sec. 2.3

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Conflict of interest

The author declares that he has no conflict of interest.

References

1. H. Preston-Thomas, *Metrologia* **27**, 3 (1990). DOI 10.1088/0026-1394/27/1/002. ; Erratum, **27**, 107
2. J.G. Hust, *Cryogenics* **9**, 443 (1969)
3. A.H. Harvey, *Int. J. Thermophys.* **42**, 165 (2021). DOI 10.1007/s10765-021-02915-9
4. Comité International des Poids et Mesures, *Metrologia* **5**, 35 (1969). DOI 10.1088/0026-1394/5/2/001
5. Comité International des Poids et Mesures, *Metrologia* **12**, 7 (1976). DOI 10.1088/0026-1394/12/1/003
6. R.L. Rusby, *J. Chem. Thermodyn.* **23**, 1153 (1991). DOI 10.1016/S0021-9614(05)80148-X

7. R.L. Rusby, R.P. Hudson, M. Durieux, *Metrologia* **31**, 149 (1994). DOI 10.1088/0026-1394/31/2/009
8. G.W. Burns, G.F. Strouse, B.W. Mangum, M.C. Croarkin, W.F. Guthrie, P. Marcarino, M. Battuello, H.K. Lee, J.C. Kim, K.S. Gam, C. Rhee, M. Chattle, M. Arai, H. Sakurai, A.I. Pokhodun, N.P. Moiseeva, S.A. Perevalova, M.J. de Groot, J. Zhang, K. Fan, S. Wu, in *Temperature: Its Measurement and Control in Science and Industry*, vol. 6, ed. by J.F. Schooley (American Institute of Physics, New York, 1992), vol. 6, pp. 537–546
9. T.B. Douglas, *J. Res. Nat. Bur. Stand.* **73A**, 451 (1969). DOI 10.6028/jres.073A.035
10. S.D. Ward, J.P. Compton, *Metrologia* **15**, 31 (1979). DOI 10.1088/0026-1394/15/1/003
11. W.L. Tew, personal communication to A. H. Harvey (2026)
12. H.F. Stimson, *J. Res. Nat. Bur. Stand.* **42**, 209 (1949). DOI 10.6028/jres.042.017
13. H.F. Stimson, *J. Res. Nat. Bur. Stand.* **65A**, 139 (1961). DOI 10.6028/jres.065A.017
14. D.R. Lovejoy, *Nature* **197**(4865), 353 (1963). DOI 10.1038/197353a0
15. G.K. Burgess, *Bur. Stand. J. Res.* **1**, 635 (1928). DOI 10.6028/jres.001.022
16. R.J. Corruccini, *J. Res. Nat. Bur. Stand.* **43**, 133 (1949). DOI 10.6028/jres.043.015
17. J.A. Hall, *Phil. Trans. Roy. Soc. London A* **229**, 1 (1930). DOI 10.1098/rsta.1930.0001
18. C. Chree, *Phil. Mag.* **45**, 205 (1898). DOI 10.1080/14786449808621127
19. R.E. Bedford, G. Bonnier, H. Maas, F. Pavese, *Metrologia* **33**, 133 (1996). DOI 10.1088/0026-1394/33/2/3
20. Bureau International des Poids et Mesures, *Metrologia* **15**, 65 (1979). DOI 10.1088/0026-1394/15/2/002
21. R.L. Rusby, M. Durieux, A.L. Reesink, R.P. Hudson, G. Schuster, M. Kühne, W.E. Fogle, R.J. Soulen, E.D. Adams, *J. Low Temp. Phys.* **126**, 633 (2002). DOI 10.1023/A:1013791823354
22. C. Pan, F. Sparasci, M. Plimmer, L. Risegari, J.M. Daugas, G. Rouille, B. Gao, L. Pitre, *Metrologia* **58**, 025005 (2021). DOI 10.1088/1681-7575/abd845
23. H.J. Hoge, F.G. Brickwedde, *J. Res. Nat. Bur. Stand.* **22**, 351 (1939). DOI 10.6028/jres.022.036
24. R.E. Bedford, M. Durieux, R. Muijlwijk, C.R. Barber, *Metrologia* **5**, 47 (1969). DOI 10.1088/0026-1394/5/2/003
25. Chambre Centrale des Mesures et Instruments de Mesure (U. R. S. S.), *Proc.-Verb. CIPM* **24**, T141 (1955)
26. G.W. Moessen, J.G. Aston, R.G. Ascah, *J. Chem. Phys.* **22**, 2096 (1954). DOI 10.1063/1.1740018
27. C.R. Barber, *Brit. J. Appl. Phys.* **13**, 235 (1962). DOI 10.1088/0508-3443/13/5/312
28. H. Plumb, G. Cataland, *Metrologia* **2**, 127 (1966). DOI 10.1088/0026-1394/2/4/001
29. K.H. Berry, *Metrologia* **15**, 89 (1979). DOI 10.1088/0026-1394/15/2/006
30. F.G. Brickwedde, H. van Dijk, M. Durieux, J.R. Clement, J.K. Logan, *Physica* **24**, S128 (1958). DOI 10.1016/S0031-8914(58)80515-7
31. F.G. Brickwedde, H. van Dijk, M. Durieux, J.R. Clement, J.K. Logan, *J. Res. Nat. Bur. Stand.* **64A**, 1 (1960). DOI 10.6028/jres.064A.001
32. S.G. Sydorik, T.R. Roberts, R.H. Sherman, *J. Res. Nat. Bur. Stand.* **68A**, 559 (1964). DOI 10.6028/jres.068A.053
33. T.R. Roberts, R.H. Sherman, S.G. Sydorik, *J. Res. Nat. Bur. Stand.* **68A**, 567 (1964). DOI 10.6028/jres.068A.054
34. J.E. Verschaffelt, *Commun. Kamerlingh Onnes Lab. Leiden* pp. Suppl. 49, 3–29 (1924)
35. H. Kamerlingh Onnes, S. Weber, *Proc. Kon. Akad. Wet. Amst.* **18**, 493 (1915)
36. W.H. Keesom, S. Weber, G. Schmidt, *Commun. Kamerlingh Onnes Lab. Leiden* pp. No. 202c, 25–37 (1929)
37. W.H. Keesom, *Proc. Kon. Akad. Wet. Amst.* **35**, 136 (1932)
38. W.H. Keesom, *Commun. Kamerlingh Onnes Lab. Leiden* pp. Suppl. 71d, 42–46 (1932)
39. G. Schmidt, W.H. Keesom, *Physica* **4**, 971 (1937). DOI 10.1016/S0031-8914(37)80194-9
40. B. Bleaney, F. Simon, *Trans. Faraday Soc.* **35**, 1205 (1939). DOI 10.1039/TF93933501205
41. Royal Society Mond Laboratory, *Proc.-Verb. CIPM* **23B**, T151 (1952)
42. J.R. Clement, *Proc.-Verb. CIPM* **26A**, T177 (1959)
43. H. van Dijk, M. Durieux, in *Progress in Low Temperature Physics*, vol. II, ed. by C.J. Gorter (Elsevier, Amsterdam, 1957), chap. 14, pp. 431–464
44. H. van Dijk, M. Durieux, *Physica* **24**, 1 (1958). DOI 10.1016/S0031-8914(58)93367-6
45. J. Engert, B. Fellmuth, K. Jousten, *Metrologia* **44**, 40 (2007). DOI 10.1088/0026-1394/44/1/006
46. B. Fellmuth, C. Gaiser, *J. Phys. Chem. Ref. Data* **54**, 013102 (2025). DOI 10.1063/5.0252532
47. L.M. Besley, W.R.G. Kemp, *Metrologia* **13**, 35 (1977). DOI 10.1088/0026-1394/13/1/007
48. M. Durieux, D.N. Astrov, W.R.G. Kemp, C.A. Swenson, *Metrologia* **15**, 57 (1979). DOI 10.1088/0026-1394/15/2/001

49. H.J. Hoge, J. Res. Nat. Bur. Stand. **44**, 321 (1950). DOI 10.6028/jres.044.029
50. R.E. Bedford, C. Prins, Physica **77**, 121 (1974). DOI 10.1016/0031-8914(74)90279-1
51. W.F. Giauque, H.L. Johnston, K.K. Kelley, J. Am. Chem. Soc. **49**, 2367 (1927). DOI 10.1021/ja01409a004
52. W.F. Giauque, H.L. Johnston, J. Am. Chem. Soc. **51**, 2300 (1929). DOI 10.1021/ja01383a003
53. W.F. Giauque, J.O. Clayton, J. Am. Chem. Soc. **55**, 4875 (1933). DOI 10.1021/ja01339a024
54. W.F. Giauque, C.J. Egan, J. Chem. Phys. **5**, 45 (1937). DOI 10.1063/1.1749929
55. D.N. Lyon, W.F. Giauque, J. Am. Chem. Soc. **71**, 1647 (1949). DOI 10.1021/ja01173a031
56. F. Henning, J. Otto, Physik. Z. **37**, 633 (1936)
57. W. Heuse, J. Otto, Ann. Physik **14**, 185 (1932). DOI 10.1002/andp.19324060207
58. W. Heuse, J. Otto, Ann. Physik **9**, 486 (1931). DOI 10.1002/andp.19314010406
59. W.H. Keesom, B.G. Dammers, Physica **2**, 1051 (1935). DOI 10.1016/S0031-8914(35)90192-6
60. W.H. Keesom, B.G. Dammers, Physica **2**, 1080 (1935). DOI 10.1016/S0031-8914(35)90196-3
61. W. Keesom, A. Bijl, Physica **4**, 305 (1937). DOI 10.1016/S0031-8914(37)80052-X
62. L.H. Adams, J. Am. Chem. Soc. **36**, 65 (1914). DOI 10.1021/ja02178a007
63. R.B. Sosman, Am. J. Sci. **250A**, 517 (1952). URL <https://earth.geology.yale.edu/ajs/1952A/517.pdf>
64. E.W. Lemmon, I.H. Bell, M.L. Huber, M.O. McLinden. NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP, Version 10.0, National Institute of Standards and Technology (2018). DOI 10.18434/T4/1502528
65. B.W. Mangum, G.F. Strouse, W.F. Guthrie, R. Pello, M. Stock, E. Renaot, Y. Hermier, G. Bonnier, P. Marcarino, K.S. Gam, K.H. Kang, Y.G. Kim, J.V. Nicholas, D.R. White, T.D. Dransfield, Y. Duan, Y. Qu, J. Connolly, R.L. Rusby, J. Gray, G.J. Sutton, D.I. Head, K.D. Hill, A. Steele, K. Nara, E. Tegeler, U. Noatsch, D. Heyer, B. Fellmuth, B. Thiele-Krivoj, S. Duris, A.I. Pokhodun, N.P. Moiseeva, A.G. Ivanova, M.J. de Groot, J.F. Dubbeldam, Metrologia **39**, 179 (2002). DOI 10.1088/0026-1394/39/2/7
66. T. Herman, M. Chojnacki, K. Hill, S. Rudtsch, I. Yang, P.P.M. Steur, R. Dematteis, G. Lopardo, F. Sparasci, C. Martin, L. Risegari, J. Widiatmo, T. Nakano, I. Saito, K.N. Quelhas, P. Giorgio, J. Sun, J. Zhang, J. Pearce, J. Gray, Metrologia **60**, 03001 (2023). DOI 10.1088/0026-1394/60/1A/03001
67. C. Gaiser, B. Fellmuth, R.M. Gavioso, M. Kalemci, V. Kytin, T. Nakano, A. Pokhodun, P.M.C. Rourke, R. Rusby, F. Sparasci, P.P.M. Steur, W.L. Tew, R. Underwood, R. White, I. Yang, J. Zhang, J. Phys. Chem. Ref. Data **51**, 043105 (2022). DOI 10.1063/5.0131026
68. J. Fischer, M. de Podesta, K.D. Hill, M. Moldover, L. Pitre, R. Rusby, P. Steur, O. Tamura, R. White, L. Wolber, Int. J. Thermophys. **32**, 12 (2011). DOI 10.1007/s10765-011-0922-1
69. J. Engert, A. Kirste, G. Wuebbeler, A. Casey, L.V. Levitin, J. Saunders, O. Hahtela, M. Gramich, J. Peltonen, J.P. Pekola, Metrologia **63**, 055002 (2026). DOI 10.1088/1681-7575/ae8e7f
70. R.N. Goldberg, R.D. Weir, Pure Appl. Chem. **64**, 1545 (1992). DOI 10.1351/pac199264101545