

How accurately can temperature be measured?

The accuracy attainable outside the standards lab is at best only moderate, even with the most careful work and frequent recalibrations.

William T. Gray and Donald I. Finch

Suppose you have been asked to measure the temperature of an object known to be at around 1000°C. Being a knowledgeable physicist, you know that the most accurate procedure is to obtain the best thermocouple you can and use it carefully, in accordance with the manufacturer's instructions. The calibration table that comes with the instrument charts emf values to the nearest microvolt, corresponding to about 0.1°C, and with practice you find you can get reproducible readings within this interval. Does this mean that you are measuring temperature to $\pm 0.1^\circ\text{C}$ accuracy?

Unfortunately not. Even with the best thermocouple, and with extreme skill and care on the part of the operator, temperatures near 1000°C cannot be measured to better than $\pm 0.3^\circ\text{C}$. In fact, unless the instrument is regularly recalibrated, errors of five or ten degrees can occur in the readings of a thermocouple that has seen some hours of use.

The situation is not much better in other temperature ranges, even with the best available instruments. A platinum resistance thermometer, although provided with a calibration table expressed to a precision of about 0.0001 degree, measures temperatures around 600°C only to ± 0.01 degree. And the best readings obtained with a "working" optical pyrometer (that is, not a primary or secondary standard) will have an uncertainty not less than $\pm 6^\circ\text{C}$.

Clearly, anyone who has to make temperature measurements should always be aware of the uncertainty in each of his readings. To make a realistic estimate of this, he needs to know: the history of use and maintenance of his working instruments; the calibration accuracy of his working instruments compared with his own standard instrument; the process by which his standard was compared with primary standards maintained by the standardizing laboratories (such as the National Bureau of Standards), and finally, the relation of these primary standards to the internationally-agreed practical temperature scale.

The temperature scale

All modern temperature measurements take as their fundamental origin the thermodynamic temperature scale. With a definition derived from the second law of thermodynamics, this scale is satisfying theoretically but not easy to realize in practice. Therefore the International Practical Temperature Scale of 1968 (IPTS-68) was chosen in such a way that temperature measured on it closely approximates what would be measured on the thermodynamic scale. This practical scale assigns values for the temperatures of 11 reproducible equilibrium states called "fixed points," and standard instruments, calibrated at these fixed points, are used to interpolate between the fixed-point temperatures. The definition of IPTS-68 includes formulas that relate the indications of calibrated standard instruments (when used in their designated temperature range) to the scale.

Making IPTS-68 available to users is a function of the various national standards institutions and other standardizing laboratories. They maintain standard instruments against which any other instrument can be calibrated without having direct recourse to the procedures of IPTS-68. In other words, a user whose thermometers, thermocouples and pyrometers have been calibrated by, say, the National Bureau of Standards does not have to set up the designated fixed points of the practical temperature scale himself. He is using IPTS-68 at one remove, relying on the Bureau's skill both in maintaining their own standard instruments and in transferring the calibrations to his own instruments. All temperature measurements discussed in this article will be considered to be traceable to the NBS.

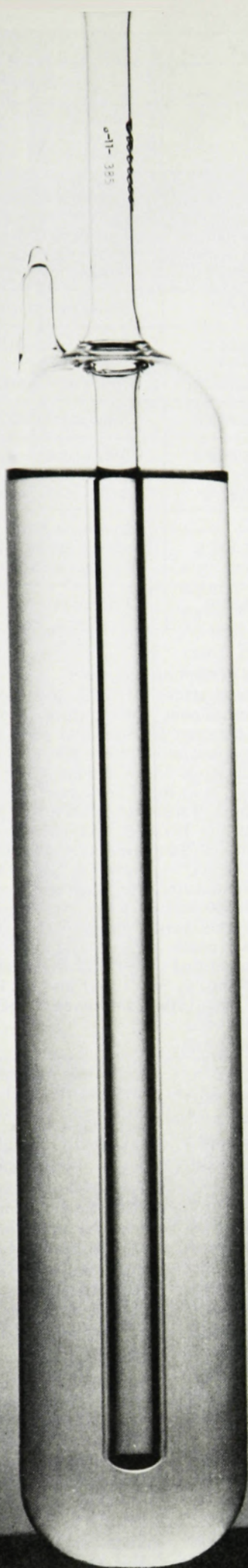
Calibration uncertainties

The standardizing laboratories have, over the years, refined their instruments and procedures to the point where they can now give their customers realistic estimates of the uncertainties in their calibrations, as referred to IPTS-68. Developments in both theory and practice have contributed to the accuracy of these assessments, as have cooperative efforts in international meetings and the exchange of standard instruments and other apparatus among the various institutions.

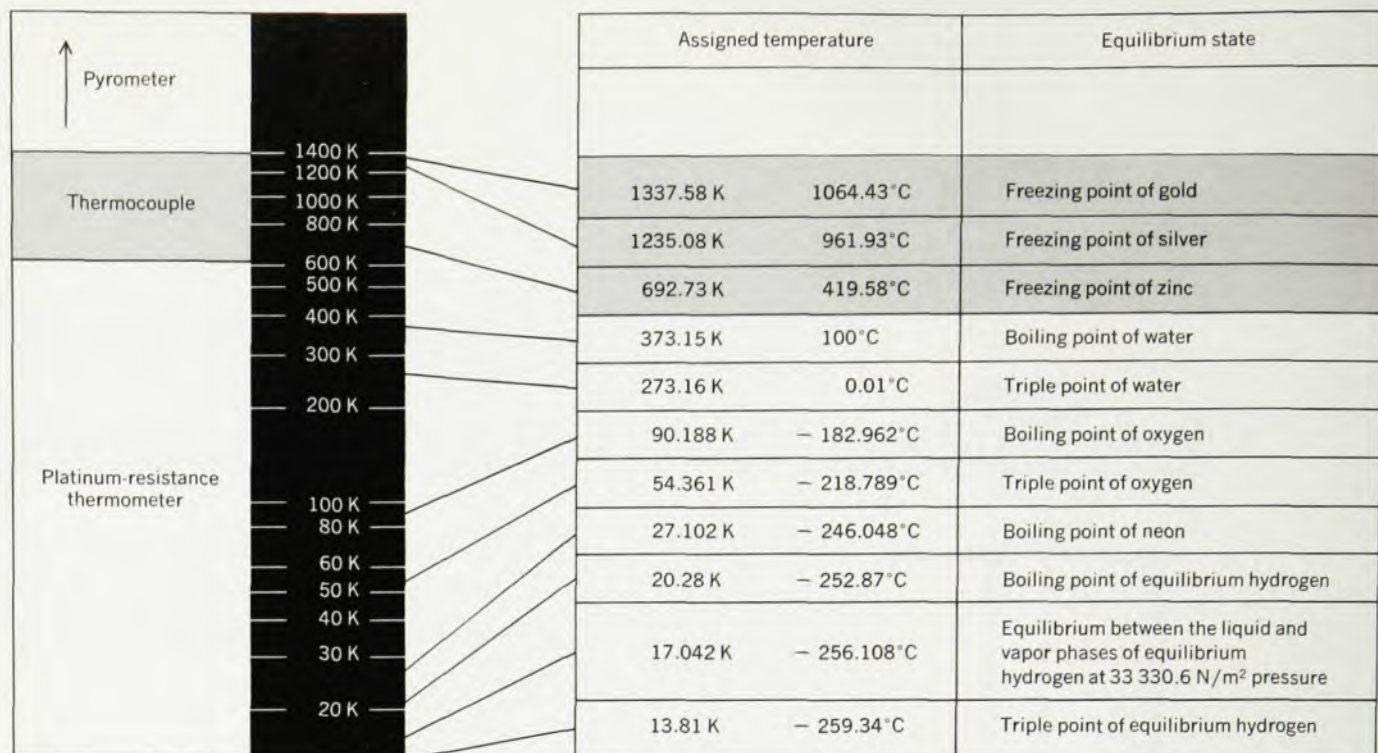
Naturally the *exact* magnitude of the uncertainty must remain unknown. Nevertheless the *probable maximum* uncertainty can be confidently estimated.

Random error can be investigated by

William Gray and Donald Finch are both with Leeds and Northrup Co, North Wales, Penna.



Triple-point cell. The equilibrium temperature between the solid, liquid and vapor phases of water (273.16 K) is one of the eleven fixed points of the International Practical Temperature Scale and is the only assigned point of the thermodynamic scale. When prepared for use, a mantle of the ice surrounds the reentrant cell and the thermometer to be calibrated is inserted into the central tube. (Photograph by J. F. Reilly.)



The International Practical Temperature Scale of 1968

The practical temperature scale adopted by the Comité International des Poids et Mesures in October 1968 consists of assigned temperature values for eleven designed equilibrium states, interpolating equations for standard platinum-resistance thermometers and thermocouples (when used in their appropriate ranges) and a form of Planck's radiation law for use above the gold point. In addition the text published by the Comité contains supplementary information on the construction and handling procedures recommended as "good practice" for the temperature-measuring instruments required by the scale, instructions on how to maintain the "fixed points," and the temperatures of 27 secondary reference points between 13.956 K (the triple point of normal hydrogen) and 3387°C (the

temperature of melting tungsten).

This scale replaces IPTS-48, the 1948 revision of the original international Temperature Scale of 1927. The differences between IPTS-68 and IPTS-48 include the extension of the low-temperature end of the scale from 90.18 K down to 13.81 K and a change in the assigned value of the coefficient c_2 in the Planck equation, as well as modifications of some of the fixed-point temperatures.

A note in the IPTS-68 text reminds readers that the 1967 Conférence Générale des Poids et Mesures adopted the name "kelvin," symbol "K," for the unit of thermodynamic temperature, with "degree Celsius," symbol "°C," as an alternative unit for a temperature interval. Note the omission of the word "degree" and the degree symbol from the kelvin scale.

The complete text of IPTS-68 is published, in English, in *Metrologia* 5, no. 2, 35 (1969) and, in French, in the *Proceedings of the 13th Conférence Générale des Poids et Mesures*, 1967-68.

making repeated measurements; a statistical analysis then enables the precision or reproducibility to be evaluated.

Systematic errors, as always, are tougher to track down. Careful study of the conditions of the measurement, perhaps combined with carefully controlled changes in those conditions, often shows how a systematic error can be minimized. For example, a deliberate change in the immersion depth of a thermometer may bring about a change in the apparent temperature and hence show the likelihood of a systematic error that should be investigated further.

Changes in the design of a measuring instrument may also be helpful. And a comparison of the values of a measurement made independently by different observers, under different conditions, with various designs of measuring in-

struments, will increase the understanding of these systematic errors and the uncertainties they produce.

Maintenance of calibrations

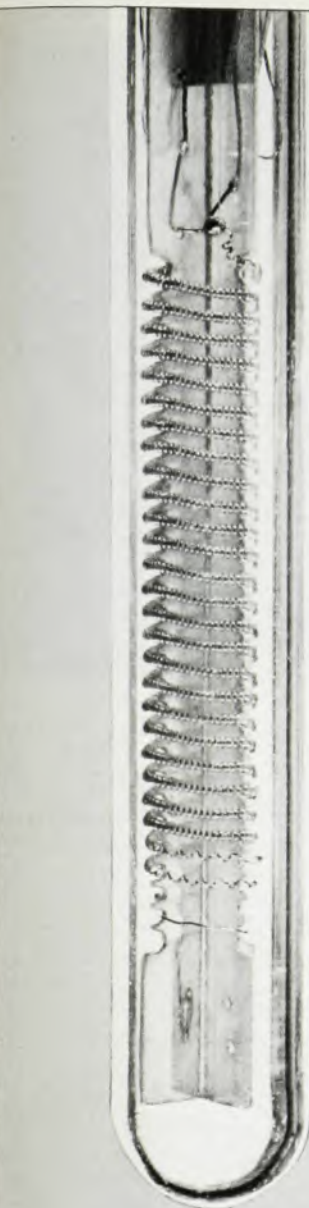
The ultimate user of a temperature-measuring instrument receives a calibration traceable directly or indirectly to his local standardizing laboratory—throughout the US, of course, this is the NBS. With the calibration he receives a realistic figure for the probable maximum uncertainty. It is the user's responsibility to maintain the calibration to this accuracy.

The instrument must be carefully handled if it is to remain as accurate as it was when delivered. For example, the resistor and leads of a platinum-resistance thermometer must not be stressed by vibration or mechanical shock, and the integrity of the environ-

ment within the glass or quartz sheath must be maintained. A thermocouple has to be kept clean and mechanically undisturbed. Similarly an optical pyrometer must be kept clean, but the cleaning has to be done with care to avoid introducing new errors.

If he uses reasonable care in making and recording his measurements, the user can soon estimate their precision (reproducibility). He will probably find the statistical scatter of these data to be much smaller than the stated maximum probable uncertainty of the calibration. Nevertheless, he must avoid jumping to the conclusion that the stated uncertainty was too conservative—that he is really measuring temperature to the accuracy indicated by the scatter in the observations.

But the user of this instrument has done nothing at this stage to establish



Platinum-resistance thermometer

NBS

The standard platinum-resistance thermometer has a four-terminal resistance element made of pure platinum wire, wound in such a way that it is free of strain initially and remains so in use. The wire diameter is usually between 0.05 mm and 0.5 mm, and the resistance of the element at 0°C is about 25 ohms.

After evacuation and baking at 450°C, the thermometer tube is filled with dry gas and sealed. Some oxygen in the gas filling will ensure that trace impurities in the platinum will remain oxidized.

The reliability of a platinum-resistance thermometer can be judged by checking the constancy of its resistance at a fixed reference temperature, for example with a triple-point cell. A commercially produced thermometer should vary by no more than 4×10^{-6} of its resistance at 0°C; the very best instruments, when handled with extreme care, will have a variation of 5×10^{-7} or less.

Table 1. Platinum-resistance Thermometers

NBS calibration uncertainty	
Oxygen boiling point (90.188 K)	$\pm 0.005^\circ\text{C}$
Triple point of water (0.01°C)	$\pm 0.0003^\circ\text{C}$
Tin freezing point (231.913°C)	$\pm 0.002^\circ\text{C}$
Zinc freezing point (419.58°C)	$\pm 0.002^\circ\text{C}$
L&N calibration	
—is expected to be within $\pm 0.002^\circ\text{C}$ of NBS calibration.	
NBS cryogenic calibrations	
10 K to 15 K	± 0.06 to 0.05°C
15 K to 90 K	± 0.02 to 0.01°C

the accuracy of the calibration; he should be continually on his guard against the possibility of deterioration of that accuracy while he works. He must check, check and re-check—by comparison with other instruments and by readings of temperatures that are known as the result of independent measurements. Continual watch must be kept for evidence of divergencies or drifts with time.

Finally, the user must always be critical of the way he works and be on the lookout for possible systematic errors that he may be introducing himself.

When he has eliminated his own observational errors (or at least reduced them to an insignificant level) and when he has sufficient experience to trust the stability of his calibrations—then, and only then, is he working to the accuracy quoted for his instruments.

Standard interpolating instruments

The International Practical Temperature Scale of 1968 covers three temperature ranges with three quite different interpolating instruments.

The standard instrument used from 13.81 K to 630.74°C is the platinum-resistance thermometer. The thermometer resistor must be strain-free annealed pure platinum. The ratio of its resistance at the boiling point of water (100°C) to its resistance at the ice point (0°C) must be not less than 1.39250. Below 0°C the resistance-temperature relation of the thermometer is found from a reference function and specified deviation equations; from 0° to 630.74°C two polynomial equations provide the resistance-temperature relation.

The standard instrument for the range 630.74°C to 1064.43°C is the platinum-10% rhodium/platinum thermocouple. The emf-temperature relation of the thermocouple is represented by a quadratic equation.

Above 1064.43°C the IPTS-68 is defined by Planck's radiation law, expressed by the relation

$$\frac{L_\lambda(T)}{L_\lambda(T_{Au})} = \frac{\exp\left[\frac{c_2}{\lambda T_{Au}}\right] - 1}{\exp\left[\frac{c_2}{\lambda T}\right] - 1}$$

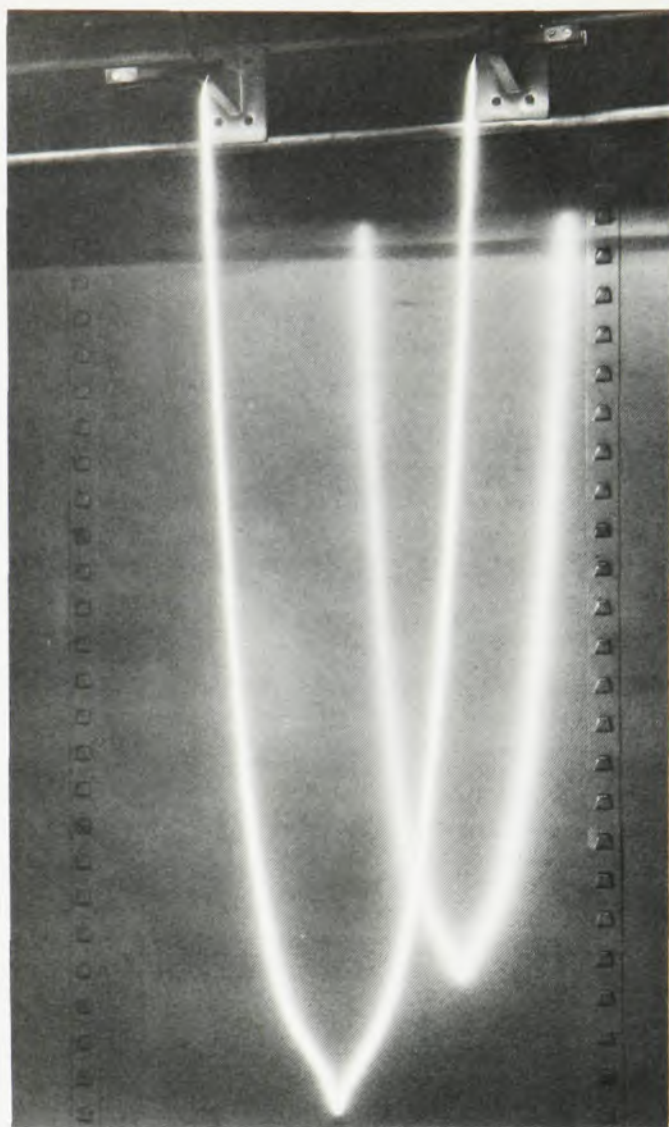
Here $L_\lambda(T)$ and $L_\lambda(T_{Au})$ are the spectral concentrations at temperature T and at the freezing point of gold, T_{Au} , of the radiance of a blackbody at the wavelength λ ; the coefficient c_2 is defined to be 0.014388 meter kelvin. Usually the standard instrument in this temperature range is an optical pyrometer, which responds to a narrow band of wavelengths in the visible-red portion of the spectrum.

The three standard instruments are quite different in nature and in the precision and the stability of their readings. Let us, then, consider separately the three ranges of IPTS-68 and the corresponding temperature measuring instruments.

Platinum-resistance thermometers

The sensitive element of the standard platinum-resistance thermometer is a compact resistor made of very pure platinum wire contained in a protecting tube. The wire hangs freely, in a strain-free condition, close to the wall of the protecting tube so that heat is easily transferred between the wire and the medium surrounding the tube. Four terminals (for "current" and "potential" leads) allow the resistance of the resistor between the branch points to be measured independently of the resistance of the leads.

To determine temperature one measures the ratio R_t/R_0 where R_t is the resistance of the resistor at the temperature to be determined and R_0 is the resistance of the resistor at the ice point. A table, computed for each thermometer when it is calibrated, relates resis-



Thermocouple

The standard thermocouple is made of two wires, one of pure platinum and the other of 90% platinum and 10% rhodium (by weight). The wires have a uniform diameter between 0.35 mm and 0.65 mm. At the gold point the emf should be $10\,300 \pm 50$ microvolts.

Before calibration the thermocouple must be annealed at 1450°C (see photograph on left) for one hour. The other photograph shows three thermocouples fused together prior to calibration; one of them is a reference standard.

tance ratios to temperature over the appropriate temperature range. This table gives resistance ratios at intervals of one degree expressed to a precision equivalent to 0.0001 degree. A linear interpolation will not introduce an additional error greater than 0.0001 degree at temperatures above -200°C .

It is customary to make calibrations by transfer from a thermometer with an NBS primary calibration to another thermometer. Fixed-point baths are convenient sources of constant temperature, but it is safer to rely on the constancy of calibration of the standard thermometer for absolute temperature values, rather than the constancy of the freezing point of the bath. Several thermometers, one of them the standard, can be compared by immersing them in succession in the crucible of a fixed-point bath during a single freeze.

Table 1 shows representative uncertainties in the primary calibration of a platinum-resistance thermometer. Part of each of these uncertainties is an allowance for systematic errors, including the differences among national lab-

oratories, the remaining part representing the effect of random errors in the measuring process.

Table 1 also indicates that we believe a transfer calibration can be made to $\pm 0.002^\circ\text{C}$. We think this is conservative and represents the maximum probable uncertainty introduced by a carefully made calibration of this type. It includes variation of the temperature in the freezing-point crucible during the freezing plateau, disturbance of the equilibrium conditions by the insertion of the thermometers and random errors of measurement. When the uncertainties of the primary calibration and the transfer are combined, the total absolute uncertainty of the calibration obtained by transfer is about $\pm 0.002^\circ\text{C}$ from 0 to 100°C , increasing to about $\pm 0.004^\circ\text{C}$ in the range from 200°C to 400°C and to perhaps $\pm 0.010^\circ\text{C}$ at 630°C . We may consider this as approximately $\pm 0.002^\circ\text{C}$ or 0.002% of the temperature in degrees C, whichever is larger.

To measure temperatures to this accuracy the resistance of the thermome-

ter coil must be measured carefully. The Wheatstone bridge and commutator designed by Mueller are commonly used in the US. The commutator is used to interchange the thermometer leads; the average of the resistance measured in the N (normal) position and in the R (reversed) position is the resistance of the thermometer resistor. The resistance of the leads is completely eliminated only if the difference in the resistance of the two leads appearing in the arms of the bridge is the same when measurements are made in the N as when measurements are made in the R position. By making a series of four measurements, at equal time intervals, in the order NRRN, the operator can look for any change in the difference of the lead resistance, and the average value of the four measurements is independent of any linear drift in this difference. The resistance may also be measured with a potentiometer, a Kelvin-type double bridge, or one of the new bridges with inductive dividers.

For accurate determinations of temperature with a platinum thermometer

Table 2. Thermocouples

	<630°C	630°C	962°C	1064°C	1450°C
Platinum, 10% rhodium-platinum thermocouples					
Calibrated thermocouples: estimated uncertainties of calibration at fixed points from NBS or L&N table	0.3°C	0.2°C 0.3°C	0.2°C 0.3°C	0.2°C 0.3°C	2.0°C
Commercial thermocouples: standard limits of error					
Grade A	1.4°C	1.6°C	2.4°C	2.7°C	3.6°C
Grade B	2.8°C	3.2°C	4.8°C	5.3°C	7.3°C
Base metal thermocouples					
NBS calibrations (table curve)	±1°C (0°C to 1100°C)				
Specific points	±0.1°C (−110°C to 300°C)				
	±0.2°C (above 300°C)				

the value of R_0 should be determined with the same bridge that measures R_t , which means that an ice bath or triple-point cell must be available. The user should redetermine R_0 frequently enough to assure himself that he has a sufficiently reliable value when measurements are made. The choice between an ice bath, in which 0°C can be realized to $\pm 0.001^\circ\text{C}$ to $\pm 0.002^\circ\text{C}$, and the triple-point cell, in which 0.01°C can be realized to $\pm 0.0002^\circ\text{C}$, depends upon the accuracy desired in the final measurement. In addition, the bridge should be recalibrated often enough to assure the user that the calibrations are reliable within the accuracy necessary for his work.

The thermometer coil must be immersed to a depth sufficient to prevent a significant error arising from transfer of heat along the thermometer leads and protecting tube. Adequacy of the immersion may be checked by varying the depth of immersion and noting whether there is a change in resistance. When a measuring current flows there is bound to be some heating of the resistor; so the same current should be used in making measurements as was used in the calibration. Sufficient time must be allowed, after the current has been turned on, for equilibrium to be established. The resistance of the thermometer may be affected by changes in the dimensions of the wire, strains in the wire, or exposure to excessive temperatures. It is particularly important to protect the thermometer from small mechanical shocks, each of which strains the wire in the platinum resistor slightly. If the resistance at a reliable fixed point is found to have changed by a significant amount, the thermometer should be recalibrated.

Thermocouples

The determination of temperature with a thermocouple consists of a mea-

surement of the emf generated in a loop formed by wires of two dissimilar metals joined at both ends. The measuring junction must be at the temperature of the object or environment whose temperature is to be determined. The reference junction is held at a fixed temperature, usually the ice point (0°C). For accurate measurements the wires must be homogeneous, unstressed, and well insulated from each other except at the junctions.

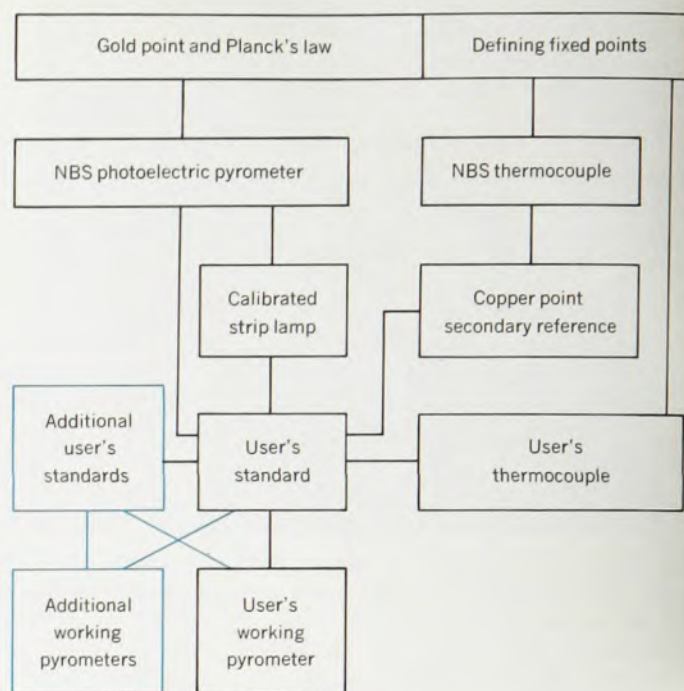
The "standard" thermocouple, by definition, is made from one wire of a 90% platinum-10% rhodium alloy, and one wire of pure platinum. This combination has been chosen because of its reproducibility and its stability in a clean oxidizing atmosphere. Table 2 shows the estimated uncertainties of calibration of standard thermocouples. Thermocouples already calibrated by NBS can be bought, or thermocouples can be purchased and sent to NBS for calibration. They must be at least 0.9144 m (36 in.) long and made of wire not less than 0.356 mm (0.014 in.) in diameter. NBS calibrations at the fixed points (the silver and gold points), and by transfer from a platinum-resistance thermometer at about 630°C, are estimated to have an uncertainty of not more than $\pm 0.2^\circ\text{C}$. A computer-generated table provided as part of the "Report of Calibration" gives emf in millivolts for integral degrees. The emf values are given to the nearest microvolt, which corresponds to about 0.1°C . Below 1100°C these emf values are estimated to have uncertainties of not more than 3 microvolts, corresponding to about $\pm 0.3^\circ\text{C}$. Above 1100°C the estimated uncertainties increase to not more than 20 microvolts (about 2°C) at 1450°C. These uncertainties are discussed in NBS Circular no. 590, "Methods of Testing Thermocouple Materials." Table 2 also shows for comparison the standard limits of error of commercial platinum,

10% rhodium-platinum thermocouples. These limits are much wider than estimated uncertainties of thermocouples calibrated by NBS.

Base-metal thermocouples are used extensively in industry for measuring and controlling temperature, and NBS will calibrate them to the uncertainties given at the bottom of Table 2. Although specific calibration points may be obtained with uncertainties comparable with those of the standard platinum, 10% rhodium-platinum thermocouples, calibration tables or curves for base-metal thermocouples have a greater uncertainty.

In the range from 630°C to about 1100°C, the most accurate measurements are made with calibrated standard platinum, 10% rhodium-platinum thermocouples, with maximum uncertainties of $\pm 0.3^\circ\text{C}$. To achieve this accuracy, care and caution must be exercised and experience must be gained through practice. Because all thermocouples deteriorate with use, a standard thermocouple should be used only as a standard, to calibrate working thermocouples by transfer. Calibrations can be transferred with a precision within $\pm 0.1^\circ\text{C}$ by placing two thermocouples together in a heavy uniform-temperature block with their beads (junctions) close together or preferably touching. Thus the calibration obtained by transfer may be expected to have an uncertainty not significantly greater than the original $\pm 0.3^\circ\text{C}$ of the standard thermocouple.

The working standard thermocouple should be long enough that the heat flow by conduction between the measuring junction and the reference junction will not disturb their respective temperatures. For the measuring junction to approach as closely as possible the temperature of the object or medium being measured, we prefer to use an exposed junction with the bead touching the object or immersed in the medium.



Succession of calibrations for a working optical pyrometer. This chart shows the chain of standards and reference points linking the user's working pyrometer with IPTS-68, with alternative additional standards in color.

During calibrations and while making accurate temperature measurements, the reference junction should be in melting ice at the ice point. A simple way to do this is to have each wire of the thermocouple in its own individual Dewar flask, attached by a screw to a small mass of copper to which an insulated copper lead has been brazed. The insulated copper leads can be run to a potentiometer capable of measuring emf reliably to ± 1 microvolt. The Dewars should be kept full of crushed or shaved ice, with the copper slugs an inch or two from the bottom, and the water produced from melting ice should be removed frequently so that there is no chance for it to accumulate below the ice.

When thermocouples are used for measuring or controlling the temperature of fuel-fired furnaces or molten baths it is often necessary to protect them from the hostile environment.

Closed-end refractory tubes and metal tubes and wells can be used; if the tubes are large enough in diameter, the working thermocouples can be checked *in situ* by inserting a working standard thermocouple alongside. This is the safest way to check a thermocouple that may have become contaminated. The temperature error in use may not be the same as the error that would be measured in a temperature equalizing block, because the gradients are not the same. A correction can be made for the error found by checking with the working standard, and the working thermocouple can still be used for control or recording purposes even though its error is several degrees. When the error has reached five or ten degrees the working thermocouple should probably be replaced; the contamination may have weakened it mechanically and it may be about to fail.

The working standard thermocouple

should be recalibrated after a few hundred hours of use (more or less, depending on conditions of use). Even in a pure oxidizing atmosphere the emf of a platinum, 10% rhodium-platinum thermocouple will drift slowly downward if it is held at a constant high temperature. This drift is caused by migration of the rhodium. For this reason the standard thermocouple should be replaced after about 1000 hours of use. It is not advisable to have this used standard recalibrated by a standards laboratory; it is better to buy a new standard. The old one can then be used as a working standard after it has been recalibrated by transfer from the new standard.

The practical details of checking a working thermocouple can best be worked out by the user himself. For example, in the factory or shop a working thermocouple is generally used with compensating leads rather than ice-baths for the cold junction; the connections of the thermocouple leads to these compensating leads should not be hotter than about 260°C and they should be at the same temperature. Compensating leads should always be suspected of causing errors of one degree or more, and whenever possible it is better to run the thermocouple all the way to the measuring instrument.

The working standard should be connected directly to a high-precision portable potentiometer with a reference-junction compensation circuit. If compensating leads must be used with the working standard these connections should be joined thermally, say by taping them together with a few layers of

Table 3. Optical Pyrometers

Estimated uncertainties of calibrated user's standards (in °C)

	800°C	1100°C	1250°C	1800°C	2800°C	3500°C
Visual optical pyrometers						
NBS extensive calibration	2.5	1.7	2	3	7	13
NBS regular calibration	4	3	4	5	8	40
L&N Report of calibration	5	5	5	7	14	25
L&N Commercial	6	6	6	10	25	50
Automatic optical pyrometers						
NBS Report of calibration	1.2	0.6	0.8	2.0	3.8	8
L&N Report of calibration	2	2	2	7	14	25



Optical pyrometer. Calibration is carried out with a light source and a standard optical pyrometer. (Photo courtesy of Leeds and Northrup Co).

insulating tape between them, and then they should be surrounded with insulating material such as glass wool.

Optical pyrometers

Above 1064.43°C, the International Practical Temperature Scale can be realized with an optical pyrometer.

The uncertainty of many temperature measurements made with visual optical pyrometers in the laboratory and shop is illustrated in Table 3. The working pyrometer has a scale that can be read to the nearest degree, and the optical brightness match can be made to a repeatability of about 1°C. So it seems that a temperature measurement is being made with an uncertainty of about 1°C, or at the most 2°C. But this is not true. The uncertainty of the calibration is greater than $\pm 2^\circ\text{C}$. At the manufacturer's plant, the calibrating procedure probably consisted of comparing the pyrometer readings with readings of a standard pyrometer at several temperatures and adjusting the pyrometer until its readings agreed with the standard to within the manufacturing tolerance, say $\pm 4^\circ\text{C}$. The secondary standard pyrometer may have had an uncertainty of as much as $\pm 2^\circ\text{C}$. The manufacturer can reach this level of uncertainty by repeated calibrations and intercomparison of standard pyrometers. After adding the manufacturing tolerance of $\pm 4^\circ\text{C}$ to the uncertainty of the standard, $\pm 2^\circ\text{C}$, we see that the uncertainty of the calibration of the working pyrometer is $\pm 6^\circ\text{C}$.

No matter how carefully the user takes his readings, and no matter how many readings he makes to obtain an

average value, he will always have this uncertainty of $\pm 6^\circ\text{C}$.

In many applications this $\pm 6^\circ\text{C}$ uncertainty is not important. The user may be making checks of a furnace temperature, which he needs to know to only $\pm 10^\circ\text{C}$. He may be reading temperatures of objects of low or variable emissivity, or there may be other sources of error that make the $\pm 6^\circ\text{C}$ uncertainty trivial. But if he is trying to make accurate temperature measurements he must remember that this is the basic uncertainty of his results.

This $\pm 6^\circ\text{C}$ uncertainty applies to the pyrometer only in its new condition. As time goes on the user cannot maintain even this degree of uncertainty unless he checks the pyrometer regularly. A check can be made by comparing a reading with a reading of the same target made with another optical pyrometer. The radiating properties of the target must approximate those of a blackbody; the filament of a tungsten strip lamp is good enough, but the wall of a furnace cavity is better. A closed-end refractory tube is an excellent target if the end is at uniform temperature.

Another method of checking the pyrometer is to read the wall of a furnace cavity, or a similar enclosure, that is at a known temperature. A convenient way to measure the wall temperature is to insert a thermocouple in the field of view of the pyrometer so that the thermocouple bead is near the target. Then, if the refractory insulation near the bead is invisible against the wall, the thermocouple reading represents the wall temperature. Checks such as

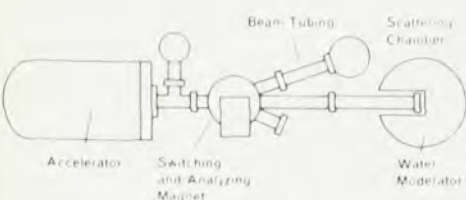
these are exploratory in nature; if made with reasonable care, they serve as assurance that nothing catastrophic has happened to the pyrometer to cause gross errors in its readings.

Maintenance of the calibration of an optical pyrometer requires keeping the optical surfaces and any electrical contacts clean. The outer surfaces of the objective lens and the eye lens should be cleaned frequently, and the other optical surfaces should be cleaned occasionally. The lamp faces have to be cleaned with extreme care. Do not rub the lamp excessively or rapidly; such rubbing might develop a static charge that could cause the filament to bow, thus ruining the lamp.

Slidewires can be cleaned with Vaseline. Place a little Vaseline on a cloth, and thoroughly work it into the cloth, clean the contacting surfaces of the slidewire with the cloth, and wipe off any excess. If necessary, repeat this procedure. If the slidewire is still not clean, use a mixture of chloroethene and isopropyl alcohol and then repeat the cleaning procedure with Vaseline. This cleaning treatment is intended to provide more positive electrical contact with the slidewire, and to reduce wear by removing gritty particles and providing lubrication.

The calibration checks and cleaning will only serve to assure the user that he is retaining the original accuracy of his calibration. Reduction of the initial $\pm 6^\circ\text{C}$ uncertainty requires the careful use of reliable standards.

If the user wants to reduce the uncertainty of his optical pyrometer readings below the $\pm 6^\circ\text{C}$ of the ordinary new



Complete Nuclear Physics Teaching Laboratory

At last! An accelerator-based teaching system for less than \$50,000. A lot less if you already have some of the electronics.

By system, we mean first, the equipment: a 400 KeV Van de Graaff accelerator, vacuum equipment, magnet, scattering chamber, detectors, radioactive sources, support electronics, pulse height analyzer, and radiation monitor.

Second, our teaching manual: 30 graded experiments in nuclear physics, explained step by step, enough to fill a 3-semester laboratory course. By then the student will have performed the fundamental experiments of nuclear physics and encountered a great deal of quantum mechanics, atomic physics, and solid state physics.

Research? Yes. In nuclear physics, solid state physics, atomic physics, and activation analysis. The magnet provides for additional research stations where your staff and graduate students can do original work.

It's everything a teaching/research system should be: simple to operate, virtually maintenance-free, easily modified for different experiments, low initial cost, expandable with optional equipment.



Our booklet, "The Van de Graaff Nuclear Physics Teaching Laboratory," shows just how this equipment and course book combine theory and practice in the modern physics curriculum. We'll be glad to send it to you.

HV HIGH VOLTAGE ENGINEERING
Burlington, Massachusetts

Name _____

Position _____

Organization _____

Address _____

Zip _____

Circle No. 19 on Reader Service Card

instrument, he can get his own standard by purchasing a new pyrometer and having it calibrated by NBS on its way to him. Or if he has an optical pyrometer that he likes, particularly if his own calibration checks have been reproducible over a period of time and have thus increased his confidence in it, he can send it to NBS for calibration. Then he will receive with the calibrated pyrometer a Report of Calibration, which contains a table giving IPTS-68 temperatures for a series of scale readings. The user can make a correction curve or he can use the table as it is to estimate corrections to the scale readings. The Report of Calibration also contains estimates of the maximum uncertainty of corrected scale readings at various temperature levels. For example, a new pyrometer may have an estimated maximum uncertainty of $\pm 3^\circ\text{C}$ near the gold point. This is not the mathematical uncertainty of the calibration as made at NBS; it includes an estimate based on experience in handling pyrometers at NBS and represents the probable condition of the calibration after the pyrometer has been put in service.

The user now has a standard optical pyrometer. He can use it to measure temperatures with much less uncertainty. But if he has to make measurements in the presence of high ambient temperature or clouds of dust and smoke, or if the pyrometer is subject to rough handling, he should have another instrument—a working pyrometer—which he can calibrate by comparing its readings with those of the standard. If done with care the calibration should not introduce an additional uncertainty of more than 1°C ; so the working pyrometer should have a total uncertainty of not more than $\pm 4^\circ\text{C}$. The figure on page 38 illustrates the succession of calibrations in this case. Again, the original uncertainties of the standard and the working pyrometer cannot be assumed to stay fixed as time goes on.

Repeated calibrations of the working pyrometer against the standard will increase confidence in both pyrometers if the agreement between successive calibrations is of the order of 1°C . After a few such repetitions, the total uncertainty of the working pyrometer is probably not more than $\pm 3^\circ\text{C}$.

If the standard pyrometer is going to be used only in the laboratory as a standard and for making precise temperature measurements, then it may be of advantage to have NBS make another type of calibration, in which the lamp current is given at a series of IPTS-68 temperatures. This calibration is most useful if it is used as the basis of a computer-generated table of current values for integral temperature degrees. Connections are available in the pyrometer control box for connecting a pair of cop-

per leads so that the filament current of the lamp can be passed through an external 1-ohm standard resistor. The ohmic drop across this resistor can then be measured with a dc potentiometer. This method provides greater precision of measurement and takes full advantage of careful optical balances.

In the laboratory, and in some special industrial applications, an automatic optical pyrometer can be used to make temperature measurements with greater accuracy than can be obtained with a visual optical pyrometer. A photoelectric detector is used to make a very precise balance between the brightness of the pyrometer lamp filament and that of the target of unknown temperature. The precision of reading is $\pm 0.1^\circ\text{C}$ or less. Table 3 shows typical estimated uncertainties of calibration of automatic optical pyrometers. The calibrations were obtained by transfer from the NBS photoelectric pyrometer. The uncertainty is well below $\pm 1^\circ\text{C}$ over most of the low range, from 800°C to 1250°C , and it increases on the higher ranges.

The estimated uncertainties from a Leeds and Northrup Report of Calibration are also given in Table 3. These data are for the calibration of an automatic optical pyrometer made by transfer from a standard automatic optical pyrometer calibrated by NBS, with both pyrometers viewing the same light source. The uncertainty introduced by this transfer, plus an allowance for possible changes in the calibration of the standard, account for the greater uncertainties.

The user of optical pyrometers has some alternative ways to maintain calibrations and so to increase his confidence in the instruments. He can use calibrated strip lamps, which have tungsten-strip filaments wide enough to use as targets; NBS calibrations are comparable in accuracy to those of visual optical pyrometers. A blackbody cavity in a constant-temperature furnace, with a standard thermocouple to determine the temperature, makes an excellent source of thermal radiation for a calibration. And NBS has recently developed a copper-point blackbody, which can be used for a one-point calibration check with an uncertainty of $\pm 0.2^\circ\text{C}$.

These alternative methods of calibration do not replace direct transfer calibrations, but they do provide a useful reassurance that the original calibration is being maintained.

* * *

This article is adapted from a talk presented at the Fifth Symposium on Temperature, held last June in Washington D. C., which was sponsored jointly by AIP, the Instrument Society of America and the National Bureau of Standards.