1. Introduction

The Comité Consultatif de Thermométrie (CCT) has always had as its chief concern the perfecting of the International Temperature Scale (ITS) and, consequently, has been occupied with thermometric measurements of the very highest accuracy. There are many laboratories in the world, including even some of the national standardizing laboratories in countries adhering to the Convention du Metre, that, while requiring temperature measurements to be related to the ITS, do not require this ultimate accuracy. In an attempt to address this need, the CCT assigned to a Working Group the task of preparing a monograph describing methods for approximating the ITS that are simpler and more practicable than the fundamental definition, giving estimated accuracies of the various approximations. That the need for this information is high can be inferred from the result of a study in the U.S.A. [Frost and Sullivan (1984)] which reveals that temperature is the most commonly measured physical variable today. The study forecast annual expenditures in the U.S.A. of \$0.9 x 10^9 on temperature measurement and control devices and instrumentation by 1988 for a real annual growth rate of 10% in the industrial temperature instrumentation market over a 5-year span. This monograph is meant to be a companion to "Supplementary Information for the ITS-90" [CCT (1990)], a forthcoming revision of "Supplementary Information for the IPTS-68 and the EPT- 76" [CCT (1983)]. The latter is directed to those who wish to realize the ITS-90 with accuracies ranging from moderately high to the very highest level; the present monograph is to give guidance to those who wish to approximate the ITS-90 using simpler techniques and for whom those levels of accuracy are unnecessarily high. It is clear that in such a monograph care must be taken to emphasize that the approximations described do not constitute official recipes for realizing the ITS-90, different from but less accurate than the fundamental definition. Such a proliferation of "official" scales would be highly undesirable.

This monograph therefore provides information on how one can approximate the ITS-90 to a modest but specified level of accuracy with a variety of techniques. It necessarily includes considerable discussion of the sensors themselves - their properties, reliability and limitations, and guidelines for proper handling and use - but this discussion is in no way exhaustive. A large literature already exists on these sensors to which the reader is referred for extensive treatments.

For a formal realization of the ITS-90, the response of (one of) the defining instruments* is measured at the appropriate defining fixed points and the thermometer is then used to interpolate temperatures between the fixed points according to the relationships specified in the definition of the scale. Methods for doing this have been outlined [CCT (1990)]. For the approximations described herein the thermometer has to be calibrated in a way that can be related to such a formal realization of the ITS-90. This can be done either by a comparison calibration or by using fixed points, approaches which differ slightly but subtly. Formerly, comparison calibrations were the most-used mechanism for dissemination of the ITS, but more and more the fixed-point method is being used. In France and in the German Democratic Republic, for example, the ITS-90 is already disseminated largely in terms of calibrated fixed point devices.

A comparison calibration (or simply a calibration) of a thermometer usually implies a direct comparison of the thermometer response with that of a calibrated defining instrument at many temperatures in some sort of isothermal environment (such as a liquid bath or a metal block in an electric furnace). Either the calibration itself, or, more usually, the calibration of the defining instrument, is carried out in a national standards laboratory or in an accredited secondary laboratory, thereby ensuring a direct link to the ITS-90. For a great many users this can be the simplest and most straightforward way to obtain direct access to the ITS-90. It can be, but is not necessarily, inexpensive. Temperatures are measured directly on the ITS-90 if the calibrated thermometer is one of the defining instruments. Under the best conditions the uncertainties in measured temperatures can be as small as those of the calibration, which in turn may be within a factor of two or three of the standards laboratory's primary realization. More generally, of course, the accuracy will be determined by the quality of the thermometer and by the measurement procedures. One disadvantage of direct calibration by a standards laboratory is that it does not constitute an independent realization of the ITS-90, if such is required. Another is that any calibration by comparison involves the transport of thermometers between laboratories, a procedure that can affect their reliability.

There are many national standards laboratories world-wide that offer a calibration service over the complete range of the ITS-90 (see Appendix A, which is not necessarily complete). Some standards laboratories are not prepared to calibrate large numbers of

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* The term "defining instrument" is used to mean any one of the standard thermometers specified in the text of the ITS-90 for interpolating between defining fixed points.

thermometers except in special extenuating circumstances; these laboratories are prepared, however, to calibrate thermometers intended to be supplied to national secondary calibration services.

Commonly, a user of large numbers of thermometers (university, factory, etc.) will not rely upon a national standards laboratory for all of its calibrations, but instead will acquire a selected number of calibrated thermometers as its secondary standards against which it will calibrate its working thermometers (or, if the user is itself another standards laboratory or an accredited calibration laboratory, its customers' thermometers). In such circumstances it is highly desirable to maintain a minimum of three secondary standards of each type that have undergone reasonably recent primary calibrations. One or, usually, two of these will become general working standards; at least one, and preferably two or more, will see very little service except for periodic checks of the calibrations of the working standards and of each other. In this way, any apparent changes in calibration can easily be traced to the offending instrument. The more secondary standards that are available, the more reliable this procedure becomes. The thermometers used as secondary standards will almost always be standard platinum resistance thermometers (SPRTs) ; germanium or rhodium-iron resistance thermometers; platinum 10% rhodium/platinum, platinum 13% rhodium/platinum, gold/platinum, or palladium/platinum thermocouples; tungsten strip-filament lamps; or infrared radiation thermometers, depending upon the temperature range required and the instrument to be calibrated. These standards should be maintained according to the procedures outlined in the "Supplementary Information for the ITS-90" [CCT (1990)]. It is recommended that fixed points (for example, triple points of water, gallium, or cryogenic substances) also be obtained so as to monitor the stability of resistance thermometers. For SPRTs this serves two important additional purposes: (a) changes in the resistance (R(t)) of an SPRT due to cold work, oxidation, strain, etc. are, to a first approximation, proportional to R(t) so that the resistance ratio $W(t) = R(t)/R(0.01\ °C)$ remains relatively unchanged. The ability to monitor a particular value of R(t), such as R(t) at a fixed point, then leads to higher temperature measurement accuracy. (b) W(t) is independent of the unit used to measure R(t) so long as all resistance values are measured with the same instrument (for example, bridge and standard resistor). Thus, laboratory measurement of resistance at a fixed point as opposed to reliance on a calibration-supplied value of resistance at that fixed point obviates the need for measurement in ohms.

The tungsten strip-filament lamp mentioned in the preceding paragraph is not itself a thermometer, but acts as a transfer device. The lamp is calibrated with a standard optical pyrometer in terms of spectral radiance temperature at a particular wavelength versus current, and this calibration is subsequently transferred to another pyrometer.

For a calibration using fixed points (which has been called a secondary realization, but this term is not recommended), the thermometer is calibrated at a number of such points (that may include both defining and secondary fixed points) and temperatures are interpolated between fixed points according to a functional (usually an empirical) relationship that experience has shown will generate values of temperature on the ITS-90 to within some specified degree of accuracy. Secondary fixed points are fixed points that are not used in the definition of the ITS-90, but which have been well-characterized, and the temperatures of which have been carefully determined on the ITS-90. Bedford et al. (1984) give recommended values of temperatures, together with an assessment of their uncertainties, for a large number of secondary fixed points. The values of temperature, which are on the IPTS-68, can be converted to the ITS-90 using the tables included here in Appendix A.

A thermometric reference material might, in some circumstances, also be used in the sense of a secondary fixed point. Caution should be exercised, however, in the use of thermometric reference materials, which differ in principle from fixed points. A fixed point (whether primary or secondary) is a phase transition temperature of a substance of extremely high purity; any two samples of the substance will exhibit precisely the same transition temperature, so long as the experimental apparatus (furnace, cryostat) is properly designed and the thermometer is in temperature equilibrium with the sample. A thermometric reference material, on the other hand, is simply a batch of certified material from which samples can be drawn; a sample of this material, when used according to a specific recipe, undergoes a phase transition at a temperature that has been previously measured and certified with a calibrated thermometer. The material need not be especially pure, and the assigned transition temperature applies only to the particular lot from which the sample is drawn. Another lot of nominally the same substance may have a different transition temperature. In this monograph the many references to secondary fixed points should not be construed as being applicable to reference materials. A thermometric sealed cell, depending upon its construction, can be used either in the sense of a fixed point or of a reference material [Pavese (1980), (1986)]. If a reference material is used as a fixed point, the value of temperature associated with it should be that given by the supplier.

The accuracies with which temperatures may be referred to the ITS-90 as a result of a comparison calibration or a calibration with fixed points are comparable; if anything, the former is the more accurate except near the fixed point temperatures unless many fixed points are used. It is difficult to make any single statement regarding the limits of accuracy that may apply. As a rough guide, the largest uncertainty for any technique described herein will be ± 0.05 K below 100 K, ± 0.2 K near and above room temperature, ± 0.5 K up to 1000 °C, and ± 1 to 2 K above. Many of the techniques, of course, may give substantially better results than this. In Table 1.1 are listed all of the thermometers discussed in this monograph, their temperature ranges under various conditions, and typical associated uncertainties.

The ITS-90 became the officially-recognized International Temperature Scale on January 1, 1990. In this monograph there are a few unavoidable references to its predecessor, the IPTS-68. Furthermore, there are undoubtedly users of this monograph who are measuring temperatures with thermometers calibrated on the IPTS-68. We emphasize that any temperature T_{68} (or t_{68}) can be converted to its equivalent value of T_{90} (or t_{90}) by use of the tables given here in Appendix A. Similarly, any previous edition of the ITS can be used to approximate the ITS-90 to within the combined accuracies of the associated conversion tables.

This monograph is divided into two parts. Part 1 includes those methods and thermometers that are considered to be best suited for directly approximating the ITS-90, and the associated calibration techniques. Part 2 deals with a number of thermometers that are important because they are widely used or are used for special purposes, but that are in general less accurate than those of Part 1, and for which temperatures measured with them must still be traced to the ITS-90. Thus, for example, approximations based upon SPRTs are described in Part 1 but treatment of industrial platinum resistance thermometers (IPRTs) is relegated to Part 2 because, although IPRTs are in wide use, they are as a class not accurate enough for approximating the ITS-90 directly in the sense defined here. International specifications for IPRTs and standard thermocouple reference tables as developed for use with the IPTS-68 are included herein. At the time of writing, corresponding specifications and tables with respect to the ITS-90 had not yet been published. Approximate equivalents can be obtained using the tables in Appendix A.

There is, naturally, a degree of overlap between the material contained herein and that in "Supplementary Information for the ITS-90" [CCT (1990)]. Methods for highly accurate fixed point realizations, for example, are described in some detail there, so will not be repeated here, but several special ways to use fixed points for approximating the ITS-90 are described in Chapter 3. On the other hand, there is some duplication in descriptions of the various sensors since all of the defining instruments are also used for secondary measurements. Except for the standard platinum resistance thermometer, there is a rather fuller description of the sensors in the present monograph. For the platinum 10% rhodium/platinum thermocouple*, in particular, which is one of the most important thermometers for approximating the ITS-90 even though it is no longer a defining instrument of the ITS, the information contained in Chapter 5 of the "Supplementary Information for the IPTS-68 and the EPT-76" [CCT-1983] has been included and substantially augmented here, and has been deleted from the revised "Supplementary Information for the ITS-90" [CCT (1990)].

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* In this monograph, specific thermocouple designations are written with the positive element first, separated from the negative element by the oblique symbol. Frequently, also, they will be written in an abbreviated form: platinum 10% rhodium/platinum will also be written as Pt10Rh/Pt, for example. Standard international letter designations, such as Type S for Pt10Rh/Pt, are also used of course.

Table 1.1: Summary of Some Properties of Most-Commonly-Used Thermometers

Thermometer	Usual Temperature Range	Thermometric Quantity	Typical Uncertainty
Germanium	1 K to 100 K	elec. resist.*	ΔT / T < 2x10-4
Rhodium-Iron	0.5 K to 30 K	elec. resist.*	0.3 mK
Platinum-Cobalt (industrial type)	2 K to 20 K	elec. resist.*	10 mK
Carbon	0.5 K to 30 K	elec. resist.*	ΔT / T < 5x10-3
Carbon-glass	0.5 K to 100 K	elec. resist.*	ΔT / T < 1 x1 0-3
Diode	4 K to 300 K	junction voltage	-50 mK
Vapour-pressure	various subranges between 0.5 K and 100 K	pressure	-1 mK
Mercury-in-glass	-50 °C to 250 °C	thermal expansion of mercury	0.1 K
Thermocouples	4 K to 2500 °C	thermoelectromotive force	
Type S	-50 °C to 1600 °C		0.3 K < 1000 °C 1 K > 1000 °C
Type R	-50 °C to 1600 °C		0.3 K < 1000°C 1 K > 1000 °C
Type B	300 °C to 1800 °C		0.5 K to 2 K
Type T	-200 °C to 350 °C		0.1 K
Type E	-200 °C to 870 °C		0.1 K < 300 K 1 K > 300 K
Type J	0 °C to 760 °C		0.5 K < 300 °C 2 K > 300 °C
Type K	-200 °C to 1260 °C		0.1 K < 200 °C 1 K 200-1000 °C 3 K > 1000 °C
Type N	0 °C to 1300 °C		0.1 K < 200 °C 0.5 K 200-1000 °C 3 K > 1000 °C
W/Re	1000 °C to 2400 °C		3-10 K

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* elec. resist. is the electrical resistance

Table 1.1: (Continued)

Thermometer	Usual Temperature Range	Thermometric Quantity	Typical Uncertainty
Thermistor	-80 °C to 250 °C	elec. resist.*	0.1 K (much better if use confined to very small temperature range)
Platinum: SPRT	14 K to 630 °C	elec. resist.*	0.5 mK
IPRT	20 K to 600 °C		50 mK
Radiation	100 °C to 3000 °C	spectral radiance of source	1 K < 1000 °C 5 K > 1000 °C

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* elec. resist. is the electrical resistance