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Possible Implications of the Principle of the '*Mise en Pratique*' in its Application to the Kelvin

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Abstract In 2005, the CIPM, in accepting CCT Recommendation T3, made a substantial change in the definition of the quantity 'temperature' by transforming the written standards for temperature (the "temperature scales") into implementations of the *mise en pratique* of the kelvin. Having considered "that the creation of a formal *mise en pratique* of the definition of the kelvin would considerably simplify and clarify statements and recommendations of the CCT concerning the realization of the definition of the kelvin and the implementation of practical temperature scales," the CIPM decision transformed the present ITS-90 and PLTS-2000 into two ways to implement the *mise en pratique*, with the possibility to further define "in due course" in the *mise en pratique* "recommendations concerning the direct determination of thermodynamic temperature." The paper presents the author's views regarding possible implications for the concept of a *mise en pratique* when applied to the kelvin beyond the present implementation. One possibility is to promote the formal use and status of realizations of the thermodynamic scale that, in practice, today only represents the physical basis of an empirical scale like the ITS-90. Another path arises from assuming that the only technical limit placed on the addition of further methods to the *mise en pratique* is that they be compatible with one another, to avoid ambiguities in the definition of the temperature values, though without the constraint of having the same, or comparable, accuracy. As a consequence, other scales that are currently considered 'approximations' to the ITS-90, with no formal status other than possibly being 'recommended' by some official body, such as the CCT WG2, could be upgraded to im-

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plementations of the *mise en pratique*, though with accuracy—and precision—inferior to that of the ITS-90. This would assist the vast majority of the users of temperature scales, and could be expected to increase the support of the worldwide thermal community for the work performed by the CCT. This possibility has so far been prevented by the need to define a single written standard at only the highest state-of-the-art accuracy level, the rest being left to sparse efforts, often devoid of traceability to the written standard.

Keywords Kelvin · *Mise en pratique* · Temperature standards

1 Introduction

With the new definition of the kelvin in 2005, approved by the Consultative Committee for Thermometry (CCT) and endorsed by the CIPM, temperature scales become implementations of the *mise en pratique* of the kelvin (see Recommendation T3 in the Appendix) [1]: the CCT, having considered "that the creation of a formal *mise en pratique* of the definition of the kelvin would considerably simplify and clarify statements and recommendations of the CCT concerning the realization of the definition of the kelvin and the implementation of practical temperature scales, ...," recommended "the creation of a *mise en pratique* of the definition of the kelvin." This formal *mise en pratique* will contain "in due course, recommendations concerning the direct determination of thermodynamic temperature, the text of the ITS-90, the text of the PLTS-2000, a Technical Annex of material deemed essential for the unambiguous realization of both the ITS-90 and the PLTS-2000, and a section discussing the differences $T - T_{90}$ and $T - T_{2000}$ together with their uncertainties..."

Therefore, the Recommendation T3 text on the *mise en pratique* of the kelvin endorsed by CIPM is not just a simple *document*, re-organizing previous information concerning indications and recommendations. It introduces and calls for a different *method* of dealing with the written standards for temperature that attributes a different meaning—though the same practical use—to the two existing ones, the ITS-90 and the PLTS-2000. Additionally, it provides the same formal status to a new "Technical Annex".

ITS-90 and PLTS-2000 have not changed their regulatory status, but the new method approved by the CIPM has relaxed some of the previous constraints placed on temperature standards:

(a) adjustments to their definitions can now be implemented by simply updating the Technical Annex. In fact, the specifications for the triple point of water and the e-H_2 fixed points of the ITS-90 have already been refined to account for isotopic effects;
(b) additions "in due course" of other methods to the *mise en pratique* is also foreseen, at present with the explicit mention to thermodynamic temperature. However, the method introduced by the CIPM *intrinsically* does not prevent the acceptance of a multiplicity of methods for the *mise en pratique*, even though they may apply to the same temperature range and have different levels of uncertainty.

Procedurally, the CCT proposes to the CIPM additions or changes to the *mise en pratique* and the CIPM, generally, accepts the proposals. Until such time as the CCT proposes such changes, proposed new implementations of the *mise en pratique* of the kelvin will remain personal opinion, as others may consider it unnecessary or undesirable to include a wider choice of methods in the *mise en pratique*.

The paper discusses the author's perspective regarding the general conditions that need be satisfied by the multiplicity of methods that might be included in the *mise en pratique*, and the novel implications that would arise from these conditions. First, furtherance of the formal use and status of the realizations of the thermodynamic scale that, thus far, only represent the physical basis of the definition of ITS-90, is illustrated. Then, the addition of present 'approximations' to the ITS-90, currently without formal status, to the *mise en pratique* is considered, with levels of accuracy—and precision—lower than that of the ITS-90.

2 Different Methods in the '*Mise en Pratique*' must be Compatible with Each Other

The basic requisite of a standard is to be unique within a given uncertainty. In the case of ITS-90, several mechanisms, usually indicated as Type 1 to Type 3 [3], give rise to non-uniqueness, which in several ranges dominates the uncertainty attributed to the scale. Type 3 non-uniqueness is related to differences in interpolating instruments of the same type (e.g., due to slightly different *R–T* characteristics of different samples of platinum; or, due to differences in the realizations of the vapor-pressure or gas-thermometer implementations; or, due to the imperfection of the mathematical model used to describe temperature as a function of the response variable of the interpolating instruments).

ITS-90 extensively uses the philosophy of 'multiple definitions:' this is another independent source of non-uniqueness that also has to be taken into account (Type 2 if different types of interpolating instruments are used, Type 1 if there is an overlapping sub-range with the same interpolating instrument).

Until 2005, the contributions to the uncertainty attributable to a scale realized according to its definition combined the above intrinsic components arising from the definition itself with the state-of-the art uncertainty of its experimental implementation. All significant deviations between realizations, detected through comparison exercises, were attributed to unresolved systematic effects, i.e., to errors in the realizations to be identified and eventually eliminated by the relevant NMI(s). To avoid unduly increasing the uncertainty of the Scale definition, the 'multiple definitions' were selected and defined to ensure close agreement with each other, i.e., to realize the same Scale within their individual uncertainty, and, to be of comparable uncertainty.

The effect of having several methods of the same 'quality' for the *mise en pratique*, defined for the same written standard, is analogous with the implementation of 'multiple definitions' in the ITS-90. In fact, the metrologist may want to avoid ambiguity by realizing the written standard according to the different methods of implementing the *mise en pratique*, within a stated uncertainty. In other words, thermometers calibrated using different methods endorsed by the*mise en pratique* should provide the same numerical value for temperature when placed together in the same isothermal enclosure, *within the stated uncertainty*. The usual way to express this concept is to say that the different implementations of the *mise en pratique* must provide *compatible* measures [4][1] in order to preserve the uniqueness of the definition of the standard.

Compatibility with one another can be considered the necessary *technical* metrological requisite of the *mise en pratique* implementations. In the author's opinion, it is also sufficient. Other requirements, such as the desire to have only methods with the lowest uncertainties or to keep the *mise en pratique* 'simple' may be dictated by what we might consider as non-scientific or 'political' arguments or by a different CIPM vision for the various *mise en pratique* describing the realizations of the SI units.

There are interesting and new implications arising from this single concept in the way that one can conceive a temperature scale. We will subdivide them into two main categories in the next two sections.

3 Comparable Quality for the '*Mise en Pratique*' Implementations: The Traditional View, but Including the Thermodynamic Scale

Traditionally, a temperature written standard, such as the ITS-90, aims to define procedures that allow the smallest state-of-the-art uncertainty to be attained. Until 2005, different procedures were defined for different ranges within the same written standard, with a possible partial overlap of the definition ranges. In addition, the PLTS-2000 has a small overlap with the other written standard, ITS-90. Therefore, the use of different measurands typical of each procedure (e.g., electrical resistance for the SPRTs and pressure for the ICVGT) [3] was limited to 'multiple definitions' in their narrow overlapping ranges.

With the *mise en pratique*, the metrologist is allowed to relax the requirement that a single definition be used to measure temperature in a certain range. Unlike the testing field, the metrologist was already able to select the method to implement a given definition of the written standard. The metrologist is now allowed much more flexibility by choosing among the definitions made available by the *mise en pratique*, and selecting the one that is more convenient in a particular institution for the realization of its standards. The only requirement for this choice is that the definition be included in the list of the allowed implementations of the *mise en pratique*: the only requirement for inclusion in the list is, in principle, that there is firm experimental evidence of the equivalence of the allowed definitions as determined by their 'compatibility' with one another.

[1] The definition of 'compatibility' according to VIM (2.47-2007) is the "property of a set of measurement results for a specified measurand, such that the absolute value of the difference of any pair of measured quantity values from two different measurement results is smaller than some chosen multiple of the standard measurement uncertainty of that difference," also noting that "metrological compatibility of measurement results replaces the traditional concept of 'staying within the error,' as it represents the criterion for deciding whether two measurement results refer to the same measurand or not. If in a set of measurements of a measurand, thought to be constant, a measurement result is not compatible with the others, either the measurement was not correct (e.g., its measurement uncertainty was assessed as being too narrow) or the measured quantity changed between measurements."

This possibility of choice applies to the important case of thermodynamic temperature, with a limit: though the thermodynamic temperature scale is *in itself unique*, it must be proven that specific realizations of it are exempt from significant systematic deviations. This requirement may limit inclusion of the thermodynamic scale in the *mise en pratique* to those ranges where it is compatible with the ITS-90 or PLTS-2000. For those ranges where a persistent incompatibility can be reduced by correcting the significant bias between the ITS-90 or PLTS-2000 scales and the thermodynamic temperature scale, inclusion may be allowed following substantiation of the uncertainty of the correction. Though it may in general be undesirable, the latter solution might be an acceptable means to include top-accuracy written standards in the *mise en pratique* whose state-of-the-art realizations cannot be easily improved.

This requirement should *not* be confused with the non-uniqueness requirement, typical of a special type of thermodynamic thermometer adopted in the ITS-90, the interpolating constant-volume gas thermometer (ICVGT). There is a basic conceptual—and practical—difference: the ICVGT is an *empirical* way[2] to use a thermodynamic thermometer: the resulting scale is by definition an *approximation* to the thermodynamic scale, as are all other parts of the ITS-90 definition [5]. Consequently, apart from the possibility of significant systematic errors in specific realizations, the lack of specific prescriptions (e.g., density of the gas) for the ICVGT implementation may lead to non-uniqueness of the implementations [6–9].

Inclusion of the thermodynamic scale among the implementations of the *mise en pratique* of the kelvin is a different case. Should this scale be included "in due time" in the *mise en pratique*, no practical and technical details for its implementation can be further specified, since they would only concern the level of attainable state-of-the-art uncertainty of its technical realizations [5].[3] Therefore, no specific implementation of the *mise en pratique* method called 'thermodynamic temperature scale' need be specified. No type of implementation can be excluded, provided that there is sufficient experimental evidence of the correctness of its uncertainty claims. This is already the case of four implementations of the thermodynamic scale (instead of the ITS-90) included in the comparison CIPM CCT-K1 [10], which supplies the required evidence; it may apply in the future to other implementations [5].

In all instances, no constraints could be placed on a laboratory for its decision to choose, as more convenient for its purposes, the implementation of the thermodynamic temperature scale instead, e.g., of the ITS-90, since there is no ranking of the *mise en pratique* implementations.

According to this philosophy, the written standards would no longer be ranked by the type of definition, but according to the level of attainable uncertainty.[4] The latter is often somewhat higher for implementations of the thermodynamic scale than for

[2] Stipulated quadratic model, three calibration points, stipulated virial correction equation.

[3] This already happens, for example, to the triple points in the ITS-90 according to the present definition, or to the realization of the vapor-pressure scales or to the ICVGT. Technical details are provided as "'Supplementary information," which now unambiguously lacks the formal status of the written standard.

[4] The expected uncertainty level will become an intrinsic specification of the written standard. Today, no mention of it is included, being implicit only in the generic requirement of a state-of-the-art uncertainty limit and of sufficient technical capability in implementing the written standard.

the empirical scales. This brings us directly to the second novel possibility introduced by the *mise en pratique*.

4 Lesser, but Compatible, Levels of Quality for the '*Mise en Pratique*' Implementations: A New Opportunity for Most Users

There is no explicit mention of this possibility in the CIPM decision, but the method introduced by the CIPM does not *intrinsically* prevent acceptance of a multiplicity of methods for the *mise en pratique*, whether for the same temperature range or for *different levels of uncertainty*.

The traditional view in the temperature field, as already pointed out, is that the written standard is intended to define only a top-level temperature scale. In 1990, even the term "practical" was removed from the name of the written standard to avoid confusion between 'empirical' and 'easy to use.' Every user needing temperature measurements of lesser quality needs to show traceability to the top-level definition, even if it is several orders of magnitude lower in uncertainty than required. In fact, all that the CCT has done to address this gap was to prepare a separate Monograph "Techniques for Approximating the ITS-90" [11], whose most recent edition dates to 1990 (a revision remains in preparation). The most recent "recommended values of secondary fixed points" dates to 1996 [12]. For alternative definitions of the temperature scale, the level of 'recommendation' has never been reached. Sometimes a critical review of published work was reported, but none of them were endorsed by the CCT, even when some ISO or regional written standards were adopted for specific thermometers (typically for industrial use, IPRTs or thermocouples).

This situation has occasionally created some difficulties, and, from time to time, the usefulness of an empirical scale as opposed to the thermodynamic one has been questioned. In the author's opinion, this may have disconnected metrologists at the national laboratory level from the user community, for whom an uncertainty of 0.1 K is often sufficient and who are not interested in the subtleties of a scale made only for sub-millikelvin uncertainties. Indirectly, this may have contributed to some present difficulties in thermal metrology. Certainly, it has discouraged investigations of methods suitable for scales of lesser quality, but traceable to the ITS-90. For at least 20 years, CCT WG2 has experienced difficulty finding reliable published material in this respect, and these studies are fewer and fewer, since no institution is willing to invest resources in them without a concrete return consisting of their use and endorsement. More recently, these difficulties were manifested in the assessment of some of the MRA CMCs for the most common services concerning thermometer calibrations.

The new possibility offered by the *mise en pratique* can bridge this gap. The key is provided by the basic requirement indicated above: from a technical point of view, different *mise en pratique* implementations need only be consistent with each other, i.e., 'compatible' with one another. This requirement does not include the need for all of them to be of the same uncertainty. Consequently, the written standard can offer a majority of its users a wider and more convenient choice of methods, formally accepted as temperature written standards, within the framework of *mise en pratique* implementations,[5] adapted to their needs or having the uncertainty best fitting their purposes. There are several possibilities, with some listed here in no particular order:

(i) use of defining fixed points with some relaxed requirements, e.g., use of SRMs for the fixed point realizations or as fixed point devices, instead of realizing thermodynamic states (e.g., [11], Sects. 3.1.2 and 3.1.4);
(ii) use of a different list of defining fixed points, or of an abridged list of them (e.g., for SPRTs—[11], Sect. 8.2—or PtRh thermocouples—[11], Sect. 9.5);
(iii) use of a stipulated number of empirical calibration temperatures instead of defining fixed points (as used in several CMCs);
(iv) use of stipulated model functions instead of a given list of calibration temperatures (e.g., using vapor-pressure thermometry with substances different from helium—[10], Sect. 6 and recent developments using dynamic measurements (heat pipes); temperature amplifier for the upper temperature range);
(v) use of a model function and defining fixed points to find the numerical values of its parameters instead of a stipulated function (e.g., in the temperature range of the superconducting fixed points—[11], Sect. 3.1.1—or, using carbide fixed points at high temperatures);
(vi) use of a different scale sub-field structure of the definition;
(vii) use of different interpolating instruments, or of different quality (e.g., IPRTs—[11], Sect. 16; base metal thermocouples—[11], Sect. 18—or noble metal thermocouples—[11], Sect. 9, and other more recent types; semiconducting thermometers—[11], Sects. 11–14 and other more recent types; two-color pyrometers);
(viii) use of a stipulated 'wire scale';
(ix) harmonized use of written standards set by other organizations.

Obviously, each of the above alternatives can be considered for inclusion in the list of the *endorsed methods for the mise en pratique* only after sufficient studies are available to prove the level of uncertainty that they provide and the fact that the Scale so defined is compatible with those defined by all the other methods formally endorsed by the *mise en pratique*.

5 Conclusions

If fully exploited, the method of the *mise en pratique* of the kelvin can provide more flexibility to the written standards concerning temperature, thereby coming closer to meeting the needs of most users. In this way, it could balance the impression that temperature metrology as practiced by the national laboratories is becoming an 'ivory tower' engaged in the pursuit of scientific subtleties far removed from their needs and interests, an impression that could arise from the decision to move toward a definition of the kelvin linked to a fundamental physical constant.

5 This is a basic difference with respect to a repository of approximations to the ITS-90, currently represented by the Monograph in [12]. These approximations have no formal status; they are not written standards. On the contrary, all implementations of the *mise en pratique* do, and share equal status with respect to the ITS-90 and PLTS-2000.

Extending the principle of ‘multiple definitions’ to a set of *mise en pratique* implementations covering 2–3 decades of uncertainties would be a step in the right direction, in the author’s opinion. This would provide standards ranked according to the level of attainable uncertainty, with the necessary and sufficient technical requirement being that all definitions are compatible.

In particular, the inclusion in the *mise en pratique* of the thermodynamic scale, at least for the temperature range where compatibility with the ITS-90 and PLTS-2000 is proven, will suppress the duality introduced since 1927, when an International Temperature Scale (ITS-27) was preferred for the definition of the international written standard, whose definition was purely empirical. In fact, from then until 2005, the international written standard has always been distinct from the thermodynamic scale.

Every laboratory would be able to choose, as more convenient for its purposes, its own implementation of the thermodynamic temperature scale instead of, for example, the realization of the ITS-90, since there is no ranking of the *mise en pratique* implementations. For the same reason, a laboratory could choose any other method allowed by the *mise en pratique* more suited to its purposes.

Appendix: Consultative Committee for Thermometry

Recommendation T3 (2005) to the CIPM

Creation of a Mise en Pratique *of the Definition of the Kelvin*
The Consultative Committee for Thermometry,
considering

- that the International Temperature Scale of 1990 (ITS-90) and the Provisional Low-Temperature Scale of 2000 (PLTS-2000) are internationally accepted practical temperature scales defining temperatures T_{90} and T_{2000} that are good approximations to thermodynamic temperature, T,
- that the uncertainty of realization of certain thermometric fixed points is limited by ambiguities in the defined isotopic composition of the materials for these fixed-points,
- that clear definitions of isotopic reference compositions will assist in the establishment of internationally compatible Calibration and Measurement Capabilities,
- that recent thermodynamic temperature measurements have refined the best estimates of the differences $T - T_{90}$ together with their uncertainties,
- that the creation of a formal *mise en pratique* of the definition of the kelvin would considerably simplify and clarify statements and recommendations of the CCT concerning the realization of the definition of the kelvin and the implementation of practical temperature scales,

recommends

- the creation of a *mise en pratique* of the definition of the kelvin containing, in due course, recommendations concerning the direct determination of thermodynamic temperature, the text of the ITS-90, the text of the PLTS-2000, a Technical Annex of material deemed essential for the unambiguous realization of both the ITS-90 and the PLTS-2000, and a section discussing the differences $T - T_{90}$ and $T - T_{2000}$ together with their uncertainties,

approval by the CIPM of the text entitled "Technical annex for the *mise en pratique* of the definition of the kelvin", adopted by the CCT at its 23rd meeting, as initial entry to the Technical Annex.

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