"Intrinsic" Standards - Are They Really What They Claim?

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At the 1998 NCSL Annual Workshop & Symposium, a meeting was held of the NCSL Intrinsic Standards Committee, which gave an opportunity for one of us (Andrew Wallard) to comment on a 1997 resolution by the Comité International des Poids et Mesures (CIPM) concerning intrinsic standards. The CIPM's resolution was that:

...The CIPM noted, with concern, a growing tendency, largely amongst manufacturers of certain scientific equipment, to claim that their products - which they refer to as "intrinsic standards" - can reproduce [realise] certain SI units at the highest levels of accuracy. Such assertions are technically misleading and CIPM deplores this trend. The Comité is clear that such claims cannot be substantiated without comparison or calibration against a well qualified and systematically investigated national standard. The Comité further asks NMIs in its member states to take this matter up with any manufacturers in their own countries with the intention of putting a stop to the practice.

This concern has grown over recent years largely because many "quantum-based" realisations of the SI units are now available commercially and come with assertions of high accuracy and, in some cases, implications that the purchase of one of these pieces of equipment could enable any user to realise an SI unit independently at the highest levels. Examples of the general approach now extend beyond quantum-based standards and as well as stabilised lasers, Josephson Junction systems now include such things as triple point temperature standards.

At the 1998 NCSL there was a long discussion of the various definitions. The ANSI/NCSL Z540-1-1994 standard states that intrinsic standards are "based on well-characterised laws of physics, fundamental constraints of nature or invariant properties of materials and make ideal stable, precise, and accurate measurement standards if <u>properly designed, characterised, operated, monitored and maintained</u>." (underlined by the authors). [1] It goes on to say that the "laboratory should demonstrate by measurement assurance techniques, interlaboratory comparisons or other suitable means that its intrinsic standard in measurement results are correlated with those of national or international standards".

In 1999 the NCSL Intrinsic and Derived Standards Committee agreed on an official definition of an intrinsic standard as:

A standard recognized as having or realizing, under its prescribed conditions of use and intended application, an assigned value, the basis of which is an inherent physical constant or an inherent and sufficiently stable physical quantity. [1]

The Committee accompanies this definition with three footnotes:

1. An intrinsic standard usually consists of a device or system based on the requirements of a documented, consensus method;
2. The value of an intrinsic standard is assigned by consensus and does not need to be established by calibration or comparison with another standard. Its uncertainty is determined by considering two components: (a) that associated with its consensus value and (b) that associated with its construction and implementation; and
3. To establish and ensure stability and/or traceablity, the value of an intrinsic standard and the uncertainty associated with its construction and implementation should be verified at appropriate intervals. Verification my be carried out either by applying a recognised, consensus test method or by intercomparisons amongst comparable standards. Such intercomparisons may be accomplished with standards in a local quality control system or with external standards including national and international standards.

We agree with the majority of the views set out in the NCSL footnotes which were relayed to the CIPM in September 1998. CIPM, whilst accepting the metrological arguments, believes that the issue needs to be debated in a more public forum and should be taken a step further.

In particular the important amplification and explanation of the definition itself, as contained in the footnotes, may be in danger of being overlooked and therefore was of further concern to CIPM. This article, the contents of which were discussed with interested parties at the 1999 NCSL, is one way of airing the issues connected with intrinsic standards and invites further comment and discussion. In essence, the Comité's 1998 opinion is that:

...the term "intrinsic standard" can be misleading and, although no term is itself ideal could, it suggests, be replaced by "quantum-based standard;" and

users, especially those in developing countries or without background experience in metrology, could be misled into thinking that the purchase of a commercial "intrinsic standard" itself would enable them to operate at the forefront of metrological capability;

There is some evidence from international comparisons of "intrinsic standards" that very substantial errors — well in excess of the claimed performance — can occur if basic good metrology practice is not followed. Indeed, in a report of Josephson Voltage Standards (Reymann et. al., IEEE Catalogue number 98CH36254, ISBN 0-7803-5018-9) refer to several sources of error which can influence the performance of "intrinsic" standards. We now recognize that quantum-based standards are not the only standards that need to come under the definition of "intrinsic" standards: we have already mentioned fixed points of temperature. In this respect the CIPM statement needs some modification.

We also have some concerns about the use of the term "consensus" in footnote 2 of the 1999 NCSL definition. In particular we do not agree with the implication in footnote 2 that "the value....is assigned by consensus and does not need to be established by calibration or with another standard." In footnote 2 we think that there is a risk of confusion between the value of the standard: for example the assigned temperature of the freezing point of zinc in ITS-90, and the realization of that standard which is treated quite correctly in footnote 3.

In establishing the value of the freezing point of zinc for ITS-90 many different processes were involved, but once the Scale was adopted this value was fixed. For the purposes of general use of the freezing point of zinc as an intrinsic standard, what matters is the content of footnote 3.

We accept that the CIPM with the assistance of its specialist Consultative Committees normally assigns an agreed (consensus) value to a SI unit or quantity, but draw attention to the fact that much more has to be done to ensure that the realisation of the unit or quantity is done reliably, consistently and carefully. Only proper use of comparisons can demonstrate equivalence and traceability. The essence of our concerns centres on the fact that comparisons are a vitally important aspect of the development of new standards, especially before their formal adoption as a realisation of an SI unit or quantity.

Comparisons invariably reveal systematic effects and aspect of performance that cannot be discovered by one standard operating independently of another. Similarly, the practical use of such standards requires that each individual realization be compared with another similar one to ensure that unsuspected errors have not arisen. We therefore urge the relevant community to pay considerable attention to comparisons. Indeed the third footnote to the NCSL definition implicitly acknowledges the need for "verification" which we take to mean a comparison as the footnote recommends. In our experience, however, the word "verification" is generally used in legal metrology circles for the process of comparing the performance of an instrument with some formal legal or regulatory specification or requirement at international, national or regional/state level.

Much of the interpretation put on definitions such as the NCSL one by inexperienced users involves an interpretation of the words used in official statements. Our intention in commenting on the definitions is to minimise the risk of misinterpretation, especially by an international audience. In the Comité, our current view is that:

- A realisation of, for example, the ITS-90, or of a voltage or resistance standard based on the Josephson or quantum-Hall effects, can only be considered a primary realisation, i.e., one at the highest metrological level if all the usual documented and published precautions are taken and whatever Guidelines established by the appropriate Consultative Committee of the CIPM are followed. These guidelines incorporate best practice and are internationally agreed. It is, of course, necessary that a full uncertainty budget be prepared.
- An independent (primary) realisation made in this way must then be linked to the national measurement system and hence to the international measurement system through a properly organised comparison between this independent standard and one held by a national metrology institute. Ideally this comparison should be a direct, high level comparison with similar standards maintained at a national metrology institute and an appropriate joint publication should be made in an accessible place in which the results are given. If the comparison is through an intermediate, accredited laboratory that can demonstrate convincing traceabilty through documented comparisons or calibrations to standards maintained at a National Metrology Institute, then the additional sources of error arise and must be fully estimated and taken into account.
- If such a comparison with a national standard is made and the results published or openly available through a peer reviewed source, then the proprietor of the

standard subsequently can claim to have traceability to the SI without a *calibration* from a national metrology institute.

We hope that this view, coming from the world's most senior international metrology body, is helpful. We are not attempting to protect, in any way, national laboratories from the legitimate and very welcome, initiatives from private companies to satisfy a genuine market need for the highest performance instruments. But we do have a responsibility to urge caution and to warn users that high level metrology is far from simple! We have also suggested a way of addressing the issue.

The CIPM's thinking on this issue is, not surprisingly, consistent with a parallel initiative by CIPM/BIPM to launch a Mutual Recognition Arrangement on Recognition of Calibration and Measurement Certificates issued by National Metrology Institutes. This MRA is directed particularly at serving the needs of the accreditation and regulatory worlds, especially where there are requirements for calibration and test which affect trade. When the MRA is signed, it will mean that there is a formal international framework within which all calibration, measurement and test certificates from the signatory NMIs are recognised at an appropriate and documented degree of uncertainty in other countries. We believe this will be a major contributor to the opening of world trade markets and the reduction of technical barriers to trade.

The way in which this MRA will be implemented bears directly on the realisation of quantities, many of them "quantum-based standards" and centres on two main processes:

1. Metrological equivalence of quantities realised in NMIs through a substantial programme of comparisons, known as key comparisons, which will establish relevant uncertainties as well as any differences between the standards as maintained by the NMIs; the results of all these comparisons will be publicly available on the BIPM key comparison data base, and

2. a quality system to give confidence that the NMIs maintain their capabilities and performance on a routine, day-to-day basis.

These comparisons — we call them "key comparisons" — are at the highest metrological level and will test NMI's abilities to realise and maintain the most important quantities and units in their field. This programme is already underway at the international as well as at the regional metrology organisation level. As the programme progresses, we expect to learn more about independent realisations of quantum-based systems ("intrinsic" standards) based on commercial apparatus. We are already finding some surprises and are learning a lot about uncertainty budgets as well as some of the systematic influences on the realisation of quantities. The point we want to stress, however, is that the National Metrology Institutes are committing themselves to a process of comparison and publication of results which is equivalent to that which the CIPM recommends for purchasers of "intrinsic standards." We are convinced that the two processes are essential and will greatly enhance user confidence in the world measurement system.

Reference

1. Ehrlich, Charles D. and Rasberry, Stanley D., Journal of Research of the National Institute of Standards and Technology, Vol. 103, Number 1, January-February 1998, p 93.

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Intrinsic and Derived Standards
A Response to the CIPM

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The world's senior metrology body, the CIPM, recently issued a Resolution regarding intrinsic standards. Dr. Andrew Wallard, Deputy Director of the National Physical Laboratory, United Kingdom, and a CIPM member, brought the resolution shown below to the July 1998 NCSL Intrinsic and Derived Standards Committee (IDSC). At that time, there was a genial discussion of CIPM concerns and also of the NCSL IDSC's definition of "intrinsic standard." While there was much more agreement than disagreement, it was apparent that differences of opinion existed between CIPM and IDSC. One of the differences concerned the use of the very expression "intrinsic standard," which CIPM believes should be replaced with some other term. This paper discusses the IDSC, its definitions for intrinsic standard, and issues raised by the Wallard and Quinn article.

The CIPM Resolution

The CIPM noted, with concern, a growing tendency, largely amongst manufacturers of certain scientific equipment, to claim that their products - which they refer to as "intrinsic standards" - can reproduce [realise] certain SI units at the highest levels of accuracy.

Such assertions are technically misleading and CIPM deplores this trend. The Comité is clear that such claims cannot be substantiated without comparison or calibration against a well qualified and systematically investigated national standard. The Comité further asks NMIs in its member states to take this matter up with any manufacturers in their own countries with the intention of putting a stop to the practice.

A Public Forum

Dr. Wallard and Dr. T. J. Quinn, Director of BIPM, jointly wrote a statement (editors note: published in this issue of *Cal Lab)* that carries the discussion about intrinsic standards forward and invites public comments on this subject. NCSL IDSC members and interested parties were kept informed of the proposed article and were given the opportunity to offer comments and suggestions along the way. Also, the authors informally discussed the article most recently at the July 1999 NCSL Symposium and Workshop.

As explained in the article, CIPM remains concerned that that some users could be misled into thinking that simply purchasing a commercial 'intrinsic standard' would enable them to operate at the forefront of meteorological capability. While Dr. Wallard and Dr. Quinn consider the NCSL IDSC definition below to be essentially correct when interpreted by trained metrologists, they take issue with the footnotes. The IDSC believes these three footnotes are essential components of the definition.

NCSL Intrinsic and Derived Standards Committee Definition: Intrinsic Standard

A standard recognized as having or realizing, under its prescribed conditions of use and intended application, an assigned value the basis of which is an inherent physical constant or an inherent and sufficiently stable physical quantity

The Committee accompanies this definition with three footnotes:

1. *An intrinsic standard usually consists of a device or system based on the requirements of a documented, consensus method;*
2. *The value of an intrinsic standard is assigned by consensus and does not need to be established by calibration or comparison with another standard. Its uncertainty is determined by considering two components: (a) that associated with its consensus value and (b) that associated with its construction and implementation; and*
3. *To establish and ensure stability and/or traceability, the value of an intrinsic standard and the uncertainty associated with its construction and implementation should be verified at appropriate intervals. Verification may be carried out either by applying a recognized, consensus test method or by intercomparisons amongst*

comparable standards. Such intercomparisons may be accomplished with standards in a local quality control system or with external standards including national and international standards.

A Difference in Viewpoint

Before discussion of specific issues, it is important to explain the IDS committee's viewpoint. IDSC exists to assist the metrology community in the practical application of intrinsic and derived standards. The publications of IDSC include a *Catalogue of Intrinsic and Derived Standards*, which lists recognized intrinsic and derived standards and their important characteristics. The IDSC also develops and publishes Recommended Practices for intrinsic and derived standards to ensure that these primary standards — intrinsic or derived — are properly applied, have adequate uncertainty analyses and quality control procedures, and are properly maintained and validated. The IDSC's charter is to

identify primary standards that are either intrinsic or derived from well-known sources, establish criteria for these standards so that they can be practically realized, and provide full traceability. For these standards, develop a Recommended Intrinsic/Derived Standard Practice (RISP) that describes the equipment, requirements, uncertainties, etc., necessary to realize the standard. Disseminate each new or revised RISP to all NCSL members.

In short, the IDSC seeks to encourage and facilitate the proper use and application of intrinsic standards. IDSC's principal objectives are to identify appropriate intrinsic and derived standards, to establish Recommended Intrinsic/Derived Standard Practices (RISP) for their use, and to obtain recognition and acceptance for these standards as valid sources of traceability.

For this reason, the IDSC concerns itself not only with state-of-the-art and the most accurate calibration systems, but also with commonplace intrinsic standards. For example, from a user's standpoint, a bowl of ice cubes and water is every bit as much an intrinsic standards as a Josephson Junction Array or a Quantum Hall effect resistance standard. The Committee's objective is that users follow appropriate practices and understand the uncertainties inherent in their particular applications. Quite a few standards have been formally identified by the IDSC as intrinsic standards and are listed below. Even though the committee is concerned with both 'intrinsic' and 'derived' standards, only 'intrinsic'standards will be discussed in this article. (Note: the definition for derived standard is currently undergoing further refinement by the IDSC). [1]

Intrinsic Standards Are Used Every Day

For the metrologist interested in calibrating dial-indicating thermometers, a container of crushed ice and distilled water is an intrinsic standard with an uncertainty much better than the resolution of the thermometers under test. Every day laboratory technicians also use distilled water to measure specific gravity and to calculate displaced volumes. In these applications, and many others, relatively pure water serves as an intrinsic standard, to the level of uncertainty required by the application. Other material properties and fundamental constants are routinely used in calibration, including the acceleration of gravity, g.

In each case, the value used for the quantity of interest is not measured but assigned from some reference, and the required uncertainty regulates whether or not a particular intrinsic or derived standard is appropriate.

Similarly, triple point of water cells and metal freezing points can be trusted to realize the desired temperature to assignable uncertainty levels. However, as the uncertainty becomes smaller, measurement assurance processes and intercomparisons must become more exacting. Metal freezing point cells can be contaminated, for example, and produce incorrect (biased) values in repeated measurements. Other intrinsic standards can also give consistent but erroneous results, and control charts will not detect such errors.

Intercomparisons, on the other hand, if properly designed and carried out, will reveal significant errors in

Listing of Intrinsic Standards from the NCSL Catalogue

- Thompson-Lampard Calculable Cross Capacitor
- Quality Factor of Capacitors or Inductors
- Josephson-array Voltage Standard
- Quantum Hall Resistance Standard
- Microwave Phase Shift
- Voltage Doubler
- Cryogenic Noise Temperature Standards
- Atomic Frequency Standards
- Wavelength
- Magnetic Field Strength
- Temperature Fixed Points
- Blackbody / Radiation Thermometry
- Liquid Manometers
- Pressure Fixed Points: CO_2 & H_2O Triple Points Water
- Angle
- Planeness and Bending of Optical Flats
- Length (Lasers &Light Sources)
- Monochromatic Optical Power

the realization of a standard, and, for that reason, are emphasized in IDSC recommended practices and in the IDSC definition, even though they are not always required.

The Level of Verification Depends Upon the Uncertainty

At the highest levels of accuracy, the IDSC agrees with CIPM that comparisons with measurements performed by national laboratories are essential. These comparisons can be either direct or indirect with another laboratory that has compared with the national laboratory. In addition, for many measurement levels, comparisons with accredited laboratories or laboratories that have documented performance may be quite sufficient. It should be noted that in many cases the uncertainty associated with the intercomparisons is limited by the properties of the artifact or process used, which may be significantly larger than the uncertainty assigned to the intrinsic standard itself.

The listing of intrinsic and derived standards from the NCSL *Catalogue* illustrates the IDSC perspective. IDSC does not require the use of only NCSL-recommended practices. RISPs published by IDSC may be used for guidance by the metrologist. In those cases where recommended practices have already been developed by some other organization (IEEE, CIPM, SPIE, AVS, ANSI, IEC, etc.), IDSC will not normally sponsor a working group to develop a RISP. In the *Cal Lab* article, Dr. Wallard and Dr. Quinn appear to state that CIPM recommended practices must be used for an intrinsic standard to be recognized as traceable and, further, that comparison to national metrology institutes is required. IDSC believes that there are additional methods that provide valid traceability and realization for intrinsic standards.

Issues Raised

1. CIPM objection to the term 'intrinsic standard.'

It is the opinion of the IDSC that the term is in such wide use and so generally applied in the metrology community that its replacement by another term can not be justified. All the proposed replacements discussed to date are also subject to misunderstanding and many (for example, "quantum standards") do not include standards currently acknowledged as intrinsic standards.

2. CIPM warns that if good metrology practice is not used, errors may go undetected. As an example, a report by Reymann et. al. is referenced.

IDSC completely agrees that errors occur if good metrology practice is not used. Josephson Junction Array intercomparisons conducted thus far have successfully identified problems and permitted their correction, exactly as these studies are designed to do. The report referenced by CIPM clearly demonstrates that Round Robin comparisons do detect errors. Any standard, not just intrinsic standards, can produce errors if it is used improperly. Intercomparisons have been proven to detect these errors.

3. CIPM takes issue with footnote 2 of the NCSL definition.

The purpose of the footnote is to explicitly state that the value of an intrinsic standard is not determined through comparison or calibration against other standards. Further, the footnote explains that uncertainties exist in the assigned value and also result from construction and operation of the system. IDSC considers the footnote an important part of the definition.

4. CIPM stresses the need for comparisons.

IDSC emphatically agrees that comparisons or verifications are essential at all levels of uncertainty. However, they do not necessarily need to include a direct intercomparison with the national laboratory. In addition, in some cases, verification of the performance of the intrinsic standard may be possible using recognized, consensus test methods (as mentioned in footnote 3).

5. CIPM states that certain electrical standards, for example, can only be considered a primary realization "... if all the usual documented and published precautions are taken and whatever Guidelines established by the appropriate Consultative Committee of the CIPM are followed."

IDSC agrees that all applicable documented and published precautions must be taken (and that uncertainty calculation must be made). The IDSCís RISPs serve this purpose. Scientifically acceptable guidelines and practices by any national organization should be considered equally valid. The source of the publication is not important, only its contents and application. It should also be noted that committees of the CIPM should not be expected to develop or maintain guidelines for many of the intrinsic standards used in the metrology community.

6. CIPM states that a formal link through direct comparison to a National Metrology Institute (NMI) is essential.

IDSC does not agree. This requirement amounts to a "calibration" and is not required if the full text of the IDSC definition is followed. Again, the application and uncertainty of the realization must be taken into account, and BIPM cannot be expected to develop or maintain standards against which many of the more mundane types of intrinsic standards might be compared. Again, consensus verification test methods may be sufficient. Finally, an indirect comparison through an accredited laboratory should be sufficient.

Conclusions

There is no substitute for intercomparisons and proficiency tests, regardless of the standard being applied. Control charts, uncertainty analyses, and comparisons with other equivalent laboratories are essential tools used in metrology. The IDSC does not believe that the performance of an intrinsic standard system must be validated through comparison to an NMI, although, if practical, such validation would be very valuable. (Josephson-array voltage standards, for example, are traditionally intercompared one against the other through the use of solid state voltage standards and may never be directly compared to an NMI standard.)

Can a laboratory purchase a JJA and realize the SI unit of voltage without reference to an NMI? Can a laboratory purchase triple point, melting point and freezing point cells as defined by ITS-90 and realize the SI unit of temperature without touching base with an NMI? Depending upon the level of uncertainty to be realized, the answer to these questions can be "a resounding yes," from IDSC standpoint. However, in all situations the laboratory must verify its uncertainty for these measurements by using recognized, consensus, test methods or documented, scientifically valid comparisons to other laboratories or NMIs.

Obviously, there are some differences between CIPM and the NCSL on this issue. Discussing the differences in a public forum will hopefully move us toward a resolution in the near future.

References

1. A derived standard is simply a primary standard which is not intrinsic. Derived standards will not be discussed in this article.
2. These constants are not, in and of themselves, intrinsic standards.

Acknowledgments

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