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A Roadmap for Thermal Metrology

J. Bojkovski · J. Fischer · G. Machin · F. Pavese · A. Peruzzi · E. Renaot · E. Tegeler

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Abstract A provisional roadmap for thermal metrology was developed in Spring 2006 as part of the EUROMET iMERA activity toward increasing impact from national investment in European metrology R&D. This consisted of two parts: one addressing the influence of thermal metrology on society, industry, and science, and the other specifying the requirements of enabling thermal metrology to serve future needs. The roadmap represents the shared vision of the EUROMET TC Therm committee as to how thermal metrology should develop to meet future requirements over the next 15 years. It is important to stress that these documents are a first attempt to roadmap the whole of thermal metrology and will certainly need regular review and revision to remain relevant and useful to the community they seek to serve. The first part of the roadmap, "Thermal metrology for society, industry, and science," identifies the main social and economic triggers driving developments in thermal metrology—notably citizen safety and security, new production technologies, environment and global

J. Bojkovski (✉)
Faculty of Electrical Engineering, Laboratory of Metrology and Quality, (MIRS/FE-LMK), University of Ljubljana, Tržaška 25, 1000 Ljubljana, Slovenia
e-mail: jovan.bojkovski@fe.uni-lj.si

J. Fischer · E. Tegeler
Physikalisch-Technische Bundesanstalt, PTB, Berlin, Germany

G. Machin
National Physical Laboratory, NPL, Teddington, UK

F. Pavese
Istituto Nazionale di Ricerca Metrologica, Divisione Termodinamica, INRIM, Torino, Italy

A. Peruzzi
NMi Van Swinden Laboratorium, NMi VSL, Delft, The Netherlands

E. Renaot
LNE-INM/CNAM, Paris, France

climate change, energy, and health. Stemming from these triggers, key targets are identified that require improved thermal measurements. The second part of the roadmap, "Enabling thermal metrology to serve future needs" identifies another set of triggers, like global trade and interoperability, future needs in transport, and the earth radiation budget. Stemming from these triggers, key targets are identified, such as improved realizations and dissemination of the SI unit the kelvin, anchoring the kelvin to the Boltzmann constant, k_B, and calculating thermal properties from first principles. To facilitate these outcomes, the roadmap identifies the technical advances required in thermal measurement standards.

Keywords Future developments · Roadmap · Thermal metrology

1 Introduction

The main objective of the iMERA project [1] is to realize the goal of a European Metrology Research Area. Within the iMERA project, every EURAMET TC[1] was tasked with producing one or more roadmaps that identified future developments in their respective field. This was done to identify strategic European metrology research activities. For thermal metrology, the technical committee tasked with identifying future thermal metrology needs was that of thermometry—TC-T.

The objectives of the roadmapping process [2] were to initiate planning and analysis within the wider community of thermal metrology experts and to present this in a form suitable for decision making. It is intended that the process of roadmapping should inform the direction of metrological research and highlight the opportunities for collaboration and cooperation in the international thermal metrology community.

The first draft of the thermal metrology roadmap was developed during the EURAMET experts meeting in Berlin in February 2006. It quickly became apparent that, because the field of thermometry is so diverse, it was not possible to cover the entire field on one diagram, so the roadmap was split into two parts: the first dealt with applied thermal measurements (thermometry and thermophysical properties) under the title "Thermal metrology for society, industry, and science", and the second dealt with more fundamental aspects of thermal metrology under the title "Enabling thermal metrology to serve future needs." A parallel roadmapping activity was performed for the satellite area of humidity dealt with by TC-T; the outcome of that roadmapping exercise is described elsewhere [3].

All the roadmaps produced under the aegis of iMERA were developed by considering the following sequence: emerging societal needs (triggers), the resulting objectives (targets), the metrological applications of basic science and technology and generic techniques to enable science and technology, and, lastly, the corresponding activities (experimental realization) to achieve the objectives.

The roadmapping exercise showed that significant improvements in thermal measurement infrastructure are required to help develop solutions to the great societal

[1] EUROMET European Collaboration in Measurement Standards. TC = Technical Committee.

challenges (e.g., environment, energy efficiency, transport) that are currently facing the EU and the world.

2 Thermal Metrology for Society, Industry, and Science

Future requirements in thermal measurements, with emphasis on their role for society, industry, and science, were identified through needs anticipated in the fields of citizen safety and security, new industries and new production technologies (e.g., multi-functional materials, micro- and nano-manufacturing), environmental issues [4], energy security and efficiency, and health. For example, we can look at citizen safety and security, which is a wide-ranging field covering critical areas as diverse as microbial safety in food processing and transport, thermal measurements in nuclear reactors, to passive fast security scanning using far-infrared (FIR) and terahertz (THz) imaging. All these areas require good underpinning thermal metrology (e.g., sintering of nuclear fuel ($\sim 1,750$ °C) is currently controlled by thermocouples prone to significant unpredictable drift. Through improved temperature measurement and control, fuel consistency would be enhanced—reducing the risk of, and in extreme cases the need for, costly fuel reprocessing and reducing the amount of contingently produced radioactive waste).

The following targets were identified to address the triggers. The need for:

- Validated databases of material properties[2] and certified reference materials.
- Simplified thermal measurements.
- Improved thermal monitoring for processes and products, and, in the long term.
- Quantum-based thermometry.

Under these targets, more technical aspects were detailed. To simplify thermal measurements, it is anticipated that there will be incremental improvements to deliver increasingly efficient calibration facilities, with the development of a diverse range of transfer standards and the potential rise of remote monitoring (e.g., internet-enabled calibration and certification) that will facilitate a step reduction in calibration costs.

To improve thermal monitoring for processes and products, it is essential that improved temperature measurement and process control (through implementing, for example, high-temperature thermocouples and fixed points) will result in optimal energy use, reduced emissions, and better product quality (minimal waste product). In addition, improvements are absolutely critical for advanced production technologies [e.g., the temperature control required for the heat treatment of advanced aerospace turbine blades is already at the limit of NMI (national metrology institute) calibration capability [5]].

In the longer term, a much clearer understanding of thermal measurements under ultra-fast dynamic conditions will be required (even at the limit of local thermodynamic equilibrium). In addition, thermal measurements will become critical to the rapidly growing nanotechnology sector, where processes are extremely sensitive to

[2] That is, the validation, through the demonstration of clear traceability to SI quantities, of the entries in existing databases or the establishment of new ones where traceability to the SI is firmly established.

thermal conditions. Work will be required to understand the meaning of temperature for low particle-number systems as well as the development of ultra-small-scale quantum-based thermometry.

To meet these objectives, significant research effort and experimental realization need to be implemented. Some of these are outlined below.

Highly efficient facilities need to be developed for rapid and improved sensor calibration and validation, including multi-compartment cells, low-temperature radiation thermometers, temperature amplifiers, and high-temperature fixed points, some or all of which may be adopted in the future to improve the efficiency of the calibration process. New high-temperature thermocouples will be developed/implemented for improved industrial process control and possibly for primary scale dissemination.

An extension to improve the calibration process for the user will result from the interaction of thermal metrology and the internet, leading to remote monitoring, calibration, and certification based on secure data protocols.

Reliable thermophysical property data are essential to evaluate on-site energy consumption, product qualification, and building energy performance. Ideally, industrial processes require multi-property characterization of materials on-process. Steady-state and transient methods for material characterization at the large and nano-scale are required.

Fast, non-intrusive screening for security and medical applications will be achieved through thermal and, in the mid-term, by THz imaging. The quality of both these techniques is strongly dependent on good thermal measurements. (For example, the medical sector, in particular, is increasingly requiring quantitative thermal image measurements to facilitate cross-center data exchange and as an aid to more reliable diagnosis [6]).

The broad applications of systems with high spatial resolution, like atomic force microscopy (AFM), scanning tunneling microscopy (STM), and scanning near-field optical microscopes (SNOM) are already being combined with thermal measurements and present a challenge regarding how to demonstrate traceability to the macroscopic scale.

Understanding the thermodynamics of low-dimensional systems and using low-noise, high-accuracy electronics (e.g., superconducting quantum interference devices and other devices based on superconductivity) will open a completely new field of thermometry. The introduction of nano-scale thermometers will extend our practical understanding of the meaning of temperature for low-number systems. In the far future, it is envisaged that mesoscopic thermometers will provide users with simple and reliable practical thermodynamic thermometry based on quantum effects, not only in applications under extreme conditions, but in daily life as well.

A variety of, but by no means exhaustive list of, enabling science and technologies have been outlined. Present-day enabling technologies can easily be described. Those in the future are speculative and strongly correlated with developments in other fields as well as developments in the field of thermal metrology. The first part of the roadmap can be seen in Fig. 1.

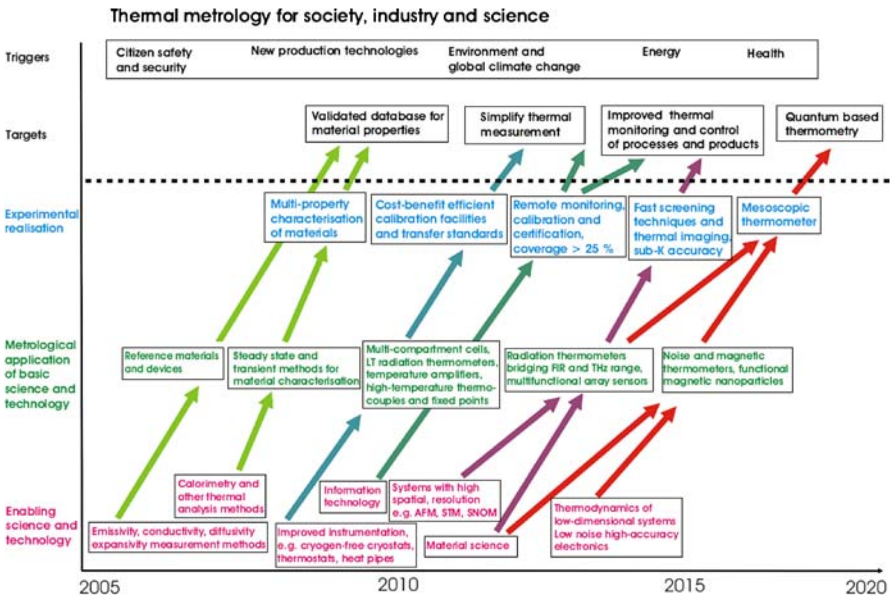

Fig. 1 Roadmap “thermal metrology for society, industry, and science”

3 Enabling Thermal Metrology to Serve Future Needs

The second part of the roadmap considering the development of the thermal metrology field, with emphasis on its role in serving future needs, was identified by considering the following triggers:

– Ever-increasing globalization is driving the requirement for a whole range of truly global standards in many areas such as manufacturing, consumer protection, healthcare, etc. in the thermometry area. Specific examples include standards for food storage and transportation and the performance of clinical thermometers. In addition, the trend to build “mirror” industrial plants in different countries demands that all sensors (not just temperature) operate in a uniform way; this requires uniform top-level metrology as well as globally accepted industrial practice.
– Essential action against global climate change (improved electricity generation [thermal, nuclear, renewables], energy efficiency [domestic and industrial], climate research), interaction with diplomatic agreements, like the Kyoto protocol, and regulations [e.g., EU Building Products Directive] demand increasingly reliable thermal measurements to be effective. (For example, it has been predicted that carbon emissions can be reduced by (15–25) Mt by 2020 in the UK, through energy efficiency measures (directly linked to improved thermal measurements) [7]).
– Future needs in transport (road, rail, shipping, air, space) will require development of new measurement techniques and instruments, more accurate thermal measurements, as well as interpretation of these (e.g., improving temperature

measurement and control of aero-engines could improve NO_x and CO_2 emissions by safely reducing the current generous safety margins—currently necessary because a 20 °C over-temperature excursion can halve the in-service life of a turbine blade).

To help address these and associated triggers, the EU Thermal Metrology community needs to achieve the following objectives to improve the foundation of thermal measurement throughout the EU.

In the relatively near term, improving the realization and dissemination of the SI unit of temperature, the kelvin, will be a clear focus of activity. Technically, this will be achieved through improved fixed points of the International Temperature Scale as well as new high-temperature fixed points, which will result in a significant reduction in uncertainty in temperature measurements from the metrology laboratory through the supply chain to the user community. This will have contingent benefits; for example, in the radiometry and photometry community, through improving the understanding of global energy balance or in the improvement of the medical treatment of clinical conditions such as psoriasis through facilitating more consistent dosing of non-ionizing radiation, or more generally to many industries such as lighting.

In the medium term, the kelvin will be redefined. The current definition relies upon the triple point of water and is therefore limited by the properties of a material substance. By redefining the kelvin in terms of the Boltzmann constant, k_B, improvements over the whole scale can be attained, both in uncertainty and in thermodynamic consistency, as explained in detail in [8]. The immediate benefits of the redefinition will be to encourage direct measurement of thermodynamic temperature without reference to, but in parallel with, the current ITS-90. The recent CIPM (International Committee for Weights and Measures—in French: Comité international des poids et mesures) resolutions (e.g., C1-2005) [9] provide stimulus for NMIs to work on improved determinations of k_B to meet the CIPM "grand challenge" of wholesale unit redefinition by 2011 [10]. Any future redefinition would, to provide continuity, have to be linked to the current International Temperature Scale of 1990, ITS-90, and this would be done through the development of the so-called mise en pratique for the kelvin [11]. In the longer term, by breaking the link with the triple point of water, the new definition will allow gradual improvements in the accuracy of temperature measurements. These can be immediately disseminated to the user community without the need for a new temperature scale. This is beneficial to users, and in particular industry, as introducing any new scale has large cost implications.

In the longer term, it may become possible to calculate thermal properties from fundamental thermodynamics and quantum mechanics, initially supporting and eventually supplanting costly measurements. This could allow new materials to be developed; for example, it is particularly important for novel insulations to drive energy efficiency improvements in the building sector (to meet upcoming building energy directive challenges), or new materials for heat engines to operate at higher temperatures, and hence more cleanly and efficiently.

To achieve the objectives and have a significant effect on the triggers, it is necessary to have a diverse and vigorous research base and this is already occurring through forming supra-national interdisciplinary project teams—often under the umbrella of

Euramet/iMERA. A diverse research base is the best way of ensuring success as several possible avenues can be simultaneously explored, not all of which may be adopted.

Current and future research is, and will be, active in the following areas: new generation of improved high-purity fixed points and high-temperature fixed points, e.g., based on metal-carbon eutectics [12], approximations of the International Temperature Scale through temperature amplifiers [13], high-temperature thermocouples, low-temperature radiation thermometers, and multi-compartment cells. Different methods for determining the Boltzmann constant k_B (acoustic, dielectric, radiometric, spectroscopic) are already coordinated in a supra-national project and efforts need to be intensified as the 2011 CIPM deadline approaches. One area of weakness in scale definition is the Provisional Low Temperature Scale PLTS-2000, with unresolved discrepancies at its foundation at the lowest temperatures, and more work should be stimulated to resolve these and improve the dissemination.

Metrological applications of basic science and technology represent steps on the roadmap toward realization of the identified objectives. These are not only limited to thermal metrology, but also require developments in other fields such as traceable chemical metrology (impurity and isotopic analyses, manufacturing of certified reference materials and superconducting reference devices); pressure, volume, dimensional, and capacitance measurements; improved interpolating instruments (better standard thermometers, better measuring instruments, etc.); improved modeling of thermal systems; etc.

A variety of enabling science and technologies has been described. Some of them need to be developed considerably because they are crucial for successful progress on

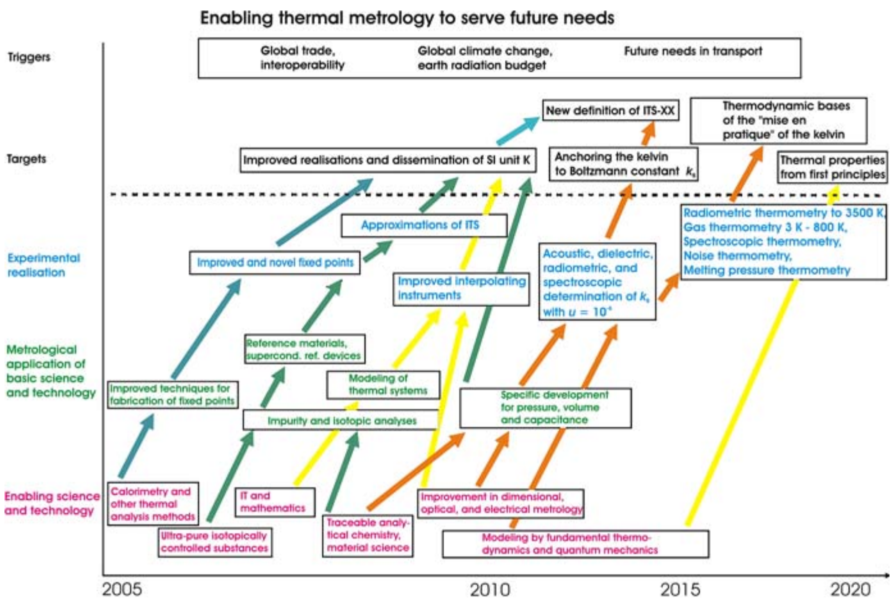

Fig. 2 Roadmap "enabling thermal metrology to serve future needs"

the respective themes (e.g., volume measurement, impurity analysis…). The second part of the roadmap can be seen in Fig. 2.

4 Conclusion

The outcomes of the roadmapping process have been to identify the current state of the art as well as to give direction to future developments in the field of thermal metrology. It is obvious that, to achieve all the identified goals, collaboration and cooperation within the international metrology community should be strengthened. This roadmap will become a useful tool for demonstrating need and rationale for further research in the field of thermal metrology development and metrology infrastructure, wherever justifications are needed at national and international levels.

It should be emphasized that these roadmaps are documents under regular review and will change in accordance with new developments in the field of thermal metrology. Responsibility for this rests with the technical committee EURAMET TC Therm, which can be contacted through the technical committee chair (currently Jovan Bojkovski, e-mail: jovan.bojkovski@fe.uni-lj.si). Comments on the present version of the roadmap, and proposals for input to future revisions, are welcome at any time. A copy of the thermal metrology roadmaps will be publicly available for the foreseeable future at http://roadmaps.wordpress.com.

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