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A European Roadmap for Thermophysical Properties Metrology

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Abstract A roadmap for thermophysical properties metrology was developed in spring 2011 by the Thermophysical Properties Working Group in the EURAMET Technical Committee in charge of Thermometry, Humidity and Moisture, and Thermophysical Properties metrology. This roadmapping process is part of the EURAMET (European Association of National Metrology Institutes) activities aiming to increase impact from national investment in European metrology R&D. The roadmap shows a shared vision of how the development of thermophysical properties metrology should

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be oriented over the next 15 years to meet future social and economic needs. Since thermophysical properties metrology is a very broad and varied field, the authors have limited this roadmap to the following families of properties: thermal transport properties (thermal conductivity, thermal diffusivity, etc.), radiative properties (emissivity, absorbance, reflectance, and transmittance), caloric quantities (specific heat, enthalpy, etc.), thermodynamic properties (PVT and phase equilibria properties), and temperature-dependent quantities (thermal expansion, compressibility, etc.). This roadmap identifies the main societal and economical triggers that drive developments in thermophysical properties metrology. The key topics considered are energy, environment, advanced manufacturing and processing, public safety, security, and health. Key targets that require improved thermophysical properties measurements are identified in order to address these triggers. Ways are also proposed for defining the necessary skills and the main useful means to be implemented. These proposals will have to be revised as needs and technologies evolve in the future.

Keywords Caloric quantities · EURAMET TC-T · Materials · Radiative properties · Roadmap · Thermal transport properties · Thermodynamic properties · Thermophysical properties

1 Introduction

A roadmap for thermophysical properties metrology was drafted during a workshop (held at NPL on 30th March 2011) by the authors on behalf of the Thermophysical Properties Working Group in the EURAMET Technical Committee—Thermometry, Humidity and Moisture, and Thermophysical Properties. EURAMET is a regional metrology organization (RMO) which coordinates the cooperation of national metrology institutes (NMI) of Europe in fields such as research in metrology, traceability of measurements to the SI units, international recognition of national measurement standards, and related calibration and measurement capabilities (CMC) of its members. Through knowledge transfer and cooperation among its members, EURAMET facilitates the development of the national metrology infrastructures.

The objectives of this roadmapping process were to identify future developments in thermophysical properties fields, to initiate planning and collaborations in the wider community of thermophysical properties metrology experts within Europe, and also to strengthen cooperation with the international scientific community. These objectives were presented in May 2012 to the task group "Thermophysical Quantities" of the Consultative Committee for Thermometry (CCT) of the Bureau International des Poids et Mesures (BIPM), for which some members are also involved as experts in other regional metrology organizations such as Asia Pacific Metrology Programme (APMP), Euro-Asian Cooperation of National Metrological Institutions (COOMET), and Inter-american Metrology System (SIM). This exercise follows a previous one performed during the period 2006–2007 and published in 2009 [1].

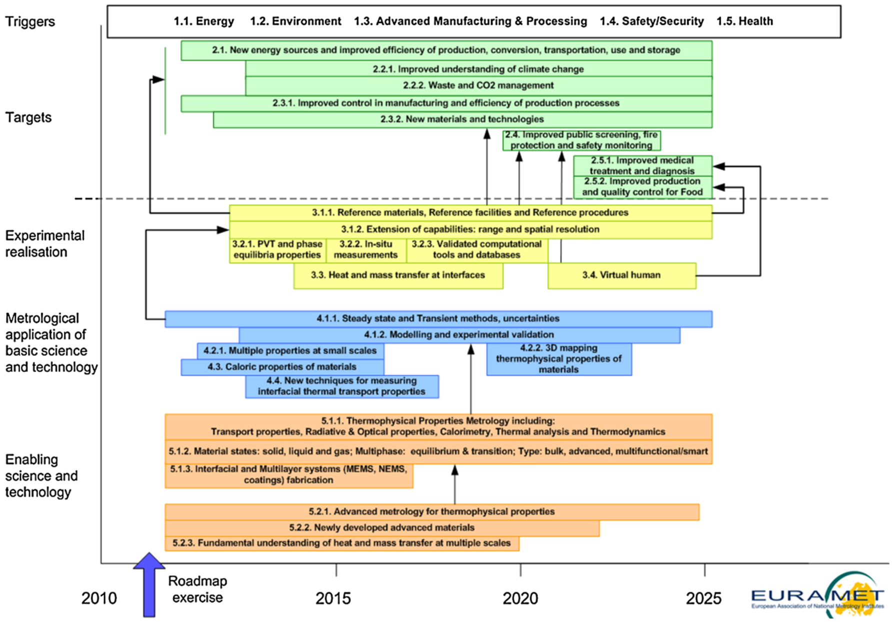

Fig. 1 Roadmap of EURAMET TC-T—thermophysical properties of materials

The roadmap was built by the experts of the Thermophysical Properties Working Group by performing the following sequence of actions:

(1) Detection of the societal and economical needs (triggers).
(2) Expression of the resulting objectives for addressing these challenges (targets).
(3) Classification of the corresponding experimental realizations to meet the targets.
(4) Formulation of the metrological application of basic science and technologies.
(5) Identification of the science and technologies for achieving the global objectives.

Since thermophysical properties metrology is a very broad and diverse topic, this roadmap has been limited to the following properties: thermal conductivity, thermal diffusivity, thermal expansion and compressibility, specific heat and enthalpy of fusion or reaction, radiative properties, and thermodynamic properties (PVT and phase equilibria properties).

The European roadmap for thermophysical properties metrology is presented in Fig. 1. The horizontal axis represents the time scale, and the vertical axis describes the different steps of the roadmapping process. All items referring to a same step have the same color. The following sections provide descriptions of the societal and scientific challenges for accomplishing the roadmap related to the thermophysical properties of materials. This roadmap is in full compliance with the objectives of "Horizon 2020—The Framework Programme for Research and Innovation" of the European Commission [2,3] by "refocusing R&D and innovation policy on major societal challenges, and strengthening the links from frontier research right through to commercialisation" [4].

2 Societal Challenges—Triggers

In line with the challenges that are outlined in Horizon 2020 [2], the working group has identified that the main social and economic triggers driving the development of thermophysical measurements are energy, environment, advanced manufacturing and processing, safety, security, and health. Thereby metrology for thermophysical properties will contribute substantially to the six priorities "Societal Challenges" which are in the focus of Horizon 2020 [5].

2.1 Energy— Secure, Clean, and Efficient

The European Union (EU) has decided to increase the renewable energy consumption up to 20 % by 2020 [2]. The development of the new alternative energy sources to fossil energy or nuclear energy has to be strengthened and accelerated. Experts of the field propose to implement new developments in the area of Thermophysical Properties Metrology (TPM) (Fig. 1: Trigger 1.1). New measuring techniques, an extended range of measurements, and a wider database should be considered for improving the efficiency of production, conversion, storage, transportation, and use of energy and also for supporting ways for saving energy (e.g., energy harvesting).

2.2 Environment—Climate—Efficient Use of Resources for Protection of Our Planet

This topic is strongly connected to energy and industry areas. Reducing emissions of greenhouse gases are at the heart of public policies. The goal is mainly to contribute to limit global warming through the reduction of energy consumption. Improving the energy efficiency of industrial processes and buildings answers major key requirements. Furthermore, sustainable technologies within the field of renewable, nuclear, and fossil energies are more and more applied and used. Therefore, one of the objectives is to optimize the use of the resources and to select and use eco-efficient materials for reducing the environmental impact. In this last case, it is highly recommended to contribute on reducing energy consumption through improving the thermal performance of building envelopes. The heating and cooling of buildings represent up to 50 % of the total energy consumption in many European countries and "constitutes" the widest potential energy saving. This way of investigation should strengthen the development and the impact of new renewable energy sources. In the field of TPM (Fig. 1: Trigger 1.2), the increase of the basic knowledge in physics and chemistry of materials, and expertise on their intrinsic properties are development priorities.

2.3 Advanced Manufacturing and Processing—Improve Industry Competitiveness in Europe

Growth in global production needs to challenge the efficiency of current processes. Materials with temperature-dependent properties are used everywhere in industry.

Needs for thermal performance measurements in developing new and innovative high-technology, high-value products are required [6].

Furthermore, appropriate methodologies with the objective to assess and qualify performances or safety of new materials, new systems, and new use of materials (e.g., in the field of electronics, building, automotive, etc.) have to be available. With regard to these challenges and considering the material aspects, each metrological methodology should be studied, developed, applied, and furthermore regularly adapted, optimized, improved, or upgraded to ensure that it always meets the needs of the end-users and of the industry practice. Research and transfer in the field of TPM have to seek to be in agreement with the final goals (Fig. 1: Trigger 1.3). New technical solutions for the measurements of thermophysical properties (TP) should be developed for ensuring the traceability and to improve the efficiency of every manufacturing process.

2.4 Safety, Security, Safe and Secure Society

The enhancing of homeland security and also the safety and security of buildings are both listed as a strong priority. Scientific and technical supports of TPM to vulnerability and risk analysis should be considered (Fig. 1: Trigger 1.4).

2.4.1 Homeland Security

Response to prevent the society from any disasters (natural or human caused) consists in studying or modeling structural effects and impacts on any infrastructures. Defense applications are also another field of regular investigations for TPM.

2.4.2 Fire Protection Technologies

Various materials as well as complex systems can be employed. Implementing the technologies implies studying, modeling, and simulating the reaction or the resistance to fire of the materials used.

2.5 Health—Longer and Healthier Lives and Safe and Secure Food Supply

Supporting innovation in health research should be the last but not the least trigger to consider (Fig. 1: Trigger 1.5).

2.5.1 Implants

Some grand challenges for improving the testing methods and the metrological characterization of biomaterials or new materials should appear during the current decade. Future engineered materials used as replacements or complements for instance of tissues, dental materials, or bones should require the development of new characterization techniques. It is easy to understand that it should be necessary for better managing the interface between tissues and biomaterials. Multiphysical approaches, modeling and development of experimental determinations of thermophysical properties of living complex systems should be investigated. This topic is clearly a case where simultaneous gathering of knowledge and expertise from different scientific areas could improve research significantly.

2.5.2 Food and Chemical Industry

As stated in Horizon 2020 [2], "90 million tons of food waste in the EU each year," the TPM need to support the investment for a safe and secure food supply. During processing, manufacturing, storage, or transportation, food products can be heated or cooled. Therefore, the capacities of one product to be heated or cooled rapidly need to be studied. Managing the thermophysical properties of the "system" and understanding the process of heat and mass transfer inside the product are challenges and one of the major aspects of the engineering properties of foods. Thus, modeling of the process requires a knowledge of both heat and mass transfer properties on changes in volume. This approach is similar for chemical products.

3 Addressing the Societal Challenges—Targets

To address these triggers, targets of thermal properties metrology were discussed and a short list was limited to five groups of targets. The targets and triggers are connected hereafter. For highlighting the connections, a non-exhaustive list of examples was identified as follows:

3.1 Energy

The R&D priorities must address challenges relative to the new energy sources and improved energy efficiency of the whole industrial chain, including production, conversion, transportation, use and storage (Fig. 1: Item 2.1):

3.1.1 Thermal Management of Buildings

Better knowledge of thermophysical materials properties and understanding and modeling of thermophysical processes should lead to less energy losses, for example, by identifying and upgrading to new working fluids for low-temperature power cycles or advanced coatings for passive solar thermal management (cf. Sect. 3.1.4). It will also lead to optimization of design, control, and processing for achieving better efficiencies.

3.1.2 Power Plants (Fossil or Nuclear Fuels)

Increasing steam temperature increases the efficiency of generators. This brings new challenges for the characterization of the required high-performance steel and high-temperature super alloys, welding, soldering, and thermal shielding (including thermal barrier coating) materials for turbines, water walls and fire walls. In the steering process of more efficient (i.e., higher temperature) power plants, smaller uncertainties in temperature measurement and a better knowledge of the thermophysical properties of the applied materials are necessary.

3.1.3 Nuclear Fusion

Linked to the operating conditions or to the risk management (safety and security of this new type of potential power plant), different scientific and technical studies should be led. For instance; the containment of the plasma, transfer of the heat generated in the walls to the turbine require to improve the knowledge of thermophysical properties of materials used under extreme conditions.

3.1.4 Solar

Different multi-technological projects of solar power plants around the world (Concentrating solar power-CSP, Concentrating Photovoltaic-PV) have been rapidly emerging during the last decade. Studies of heat generated from solar radiation, thermal efficiency of absorber materials, storage media for seasonal changes and night periods, insulation and envelopes of buildings associated with the radiative aspects and passive solar gain represent as much examples of scientific researches that drive the metrology of thermophysical properties of materials [7]

3.1.5 Energy Storage

Two main fields have to be investigated:

Storage of thermal energy: for instance, latent heat storage systems based on the use of phase-change materials (e.g., paraffin waxes, hydrated salts...) require new metrological researches.

Storage of electricity: for instance, the thermal management of batteries in confined environment, especially lithium based on cars, conversion into hydrogen, methane, synthetic gas require firstly new metrological characterizations/methodologies of systems and secondly more accurate measurements of the thermophysical properties of materials produced or consumed.

3.2 Environment

The main objective is to develop or strengthen improved understanding of climate change and waste and CO_2 management (Fig. 1: Items 2.2.1, 2.2.2). To underline the ways to investigate, several topics have been discussed. The main following topics are presented as examples.

3.2.1 Reduction of Carbon Dioxide Emissions

The reduction of carbon dioxide emissions needs to go through the design and testing of new innovative generation of fuels or energy production, a better control of industrial waste but also by improving the energy efficiency of processes and buildings. This is an immediate need, which implies an excellence in TPM for developing reference skills, diagnosis tools applied to new advanced technological materials.

3.2.2 Low-Carbon Vehicles and Infrastructures

The “TPM” community should be able to help the automotive industry for breaking potential barriers and also for accelerating the dissemination of the emerging low-carbon vehicle technologies:

- Improving conversion of chemical energy into mechanical work.
- Reducing fuel consumption in cars using thermally optimized engines.
- Investigate higher combustion temperature, less heat losses, recovering waste heat using thermal-electric devices, etc.

As a result, the air quality will be improved, and the dependency toward fossil fuels will be reduced.

3.2.3 Nuclear

The next generation of reactors, especially future high-temperature designs, could become an important low-carbon alternative to fossil fuels as a source of process heat. Furthermore, waste management will remain a critical issue for a long period, as well as the decommissioning of stopped nuclear reactors. These topics will continue to require R&D and technical expertise.

Reliable thermophysical properties data useful for the thermal management of the nuclear infrastructure or for storage and disposal of nuclear waste are therefore crucial.

3.3 Manufacturing—Processing (Fig. 1: Items 2.3.1, 2.3.2)

3.3.1 Improved Control and Efficiency of Process and Production and New Materials and Technologies

Developments are to provide industries with reliable thermal properties design data and knowledge of heat transfer in various materials. The objective is to enable them to optimize their product design and thermal control of the process, and, therefore, to achieve improved control and efficiency of the production process; to have improved efficiency of energy production, use, and storage; and to confidently choose the newly developed materials and technologies.

For instance, the implementation of advanced, high-performance refractories and insulation products for high temperatures is essential for European process industries to reduce losses of high-quality energy and to develop thermal management systems in heat-intensive engineering, such as thermal shields in nuclear and space applications. It is particularly important for novel insulations to drive energy efficiency improvements in the industrial installation and building sectors to meet energy directive challenges.

3.3.2 Other Examples of Awaited Developments

The thermal characterization of materials is also essential for supporting high-performance manufacturing, e.g., in the following applications: compatibility between mechanical and thermal properties of base materials and hard layers (e.g., for milling), prediction of heat treatment (diffusion, building of crystallites, and anisotropy), nanotechnologies, interfaces, surface morphologies, and thin films.

3.4 Safety, Security

Improved public screening, fire protection, fire safety engineering, and safety monitoring are the main research topics to be investigated.

3.4.1 Public Screening Systems

New screening technologies for screening passengers at airport checkpoints are regularly tested and upgraded. Advanced imaging technologies (AIT) systems are more and more widely deployed. This technique is considered as a full-body scanner or a body imaging system. Nevertheless, this method does not detect easily explosives. As a consequence, a new request arising is how to implement technologies and procedures for screening passengers for explosives. It has been envisaged that it should be possible to perform testing and technical assessments on screening technologies or to develop models based on thermophysical knowledge.

3.4.2 Fire Protection

With regard to the trigger numbered 1.4, to implement fire protection needs, it is required to better manage the data on thermophysical properties of materials and implement or improve reference measurements and methods as well as standards applied.

3.4.3 Safety Monitoring

Controlling supervision of nuclear-power plant sites, also in the case of accidents, can be considered as a part of this field. For instance, the construction of the future fusion reactors or even the different generations (I–IV) of fission reactors requires the development or the improvement of new structural materials. These materials and systems should be able to bring under control any damage at elevated temperatures resulting from the possible fusion/fission reactions.

In the case of nuclear decommissioning and waste management, the objective is to support hazard reduction. The planned transport and storage of nuclear waste during current and future decommissioning will require a very much higher level of traceability and international infrastructure. Thermophysical-property measurements providing the input data for thermal modeling (e.g., radiative properties and thermal transport properties of materials for containers) have to be improved or strengthened.

3.5 Health

Improved medical treatment and diagnosis/improved production and quality control for food (Fig. 1: Items 2.5.1, 2.5.2): it has been identified that the contribution to better healthcare could consist of supporting technical realizations or modeling validations of integrated medical systems or (bio)-systems dedicated to medicine, food, or the chemical industry.

3.5.1 Medical Area

The developments in TPM /metrology can contribute to strengthen the quality and performance of implants. Successful industrial competition in this sector requires a high degree of quality and high technical performance. Control of products and processes through manufacturing are on the critical path of this need. Knowledge of the thermophysical parameters (thermal expansion, thermal behavior of the materials used, etc.) is therefore critical. Some needs in the medical area are also linked with the study of physicochemical properties (temperature dependence) of living tissues.

3.5.2 Better Production Processes in Food or Chemical Industry

In the fields of food or chemical industries, the requests are related to thermophysical properties data for modeling of chemical synthesis (including thermodynamic data, especially enthalpy of formation), and to metrological analysis of *ab initio* methods for calculating thermodynamic data and reactivities—same approach for semi-empirical techniques or purely empirical techniques (group contribution theories).

4 Experimental Realization

Priorities for the experimental realizations to be made are distributed in four families and listed as follows (Fig. 1: Items 3.1.1–3.4):

- Items 3.1.1 and 3.1.2: It is planned to extend relevant measurement capabilities: range and spatial resolution, sample dimensions, under specific environmental conditions, vacuum, etc.
- This stage will be completed by reducing the uncertainty of established measurement capabilities. New reference facilities and new reference material candidates as well as the standardization of associated well-established measurement procedures will be investigated.
- Items 3.2.1–3.2.3: Three subfields to be investigated are proposed: facilities related to PVT properties, implemented and validated computational tools (including databases), and development of traceable portable instrumentation incorporating new sensors dedicated to on-site measurements.
- Item 3.3: The development of new measurement facilities for studying heat and mass transfer in interfacial systems (at micrometer and nanometer scales) is proposed.
- Item 3.4: It is planned to lead scientific projects for implementing R&D in the field of virtual human.

The development of new steady-state and transient methods at higher temperatures and also at micrometer and nanometer scales, thorough uncertainty analysis for transient techniques, and validated heat transfer models in complex advanced materials will lead to extended thermophysical properties measurement capability at higher temperatures and also at extended scales (from macrometer to nanometer). These developments will also lead to the development of certified reference materials and new European measurement standards and best practice procedures. Certified reference materials will be needed to provide traceability for industries and to calibrate and check the instruments and measurement techniques used in industries and academic laboratories. Reference materials are also required to aid in the investigation of anomalies between reference laboratories and different measurement techniques. They are essential tools to improve European equivalence.

To achieve these goals, it should be necessary to develop, implement, or investigate:

– Reference materials normally able to cover all or most of the main quantities (thermal diffusivity, thermal conductivity, emissivity, thermal expansion, specific heat, heat of fusion/transition/reaction, wetting behavior, surface tension, etc.) under all main critical conditions (temperature, pressure, atmosphere, and size (multi-scales)).
– Methods to qualify new measuring techniques (to be identified) and to establish their traceability.
– Methods for modeling thermophysical quantities.

5 Metrological Application of Basic Science and Technology

Priorities for the metrological application of basic science and technology are distributed in four families and listed as follows (Fig. 1: Items 4.1.1–4.4):

- Items 4.1.1 and 4.1.2: In this section, R&D should be focused on steady-state and transient methods, on modeling associated with experimental validation, and improvement of uncertainties that can be achieved.
- Items 4.2.1 and 4.2.2: The study of multiple properties at small scales and 3D mapping of thermal properties of materials will be important challenges during the next decade.
- Item 4.3: The study of caloric properties of materials will be pursued. One objective should be to complete the metrological scales and to investigate new materials.
- Item 4.4: New techniques for measuring interfacial thermal transport properties including thermal contact resistance and thermal effusivity will be developed.

At high temperatures, there is a need to develop new measurement techniques for thermal transport properties, using both steady-state and transient methods. For instance, there is currently large scatter in high-temperature thermal-conductivity measurement data, especially for highly heterogeneous materials [8,9].

Steady-state methods use a simple principle but require extensive engineering to make accurate thermal-conductivity measurements. Their advantage is that the measurement uncertainty analysis is straightforward. Therefore, steady-state methods are often used in developing thermal-conductivity reference materials to provide traceability for industries. However, steady-state thermal-conductivity measurements at high temperatures face challenges in material and sensor degradation, and require advances in new materials, temperature sensors, and also new techniques. In contrast, transient methods use relatively simple measurement techniques but rely on complicated mathematic models. This has meant that the measurement uncertainty analysis according to the Guide for the Expression of Uncertainty in Measurement (GUM) [10] needs further investigation.

The modeling of heat transfer in various complex materials in steady-state and transient conditions also needs to be validated experimentally. This would require the improvement of both measurement techniques and a fundamental understanding of heat transfer in complex materials.

The underpinning metrologies for thermal transport properties at micrometer-to-nanometer scales are needed to support the R&D and manufacturing of new high-tech innovative materials and devices. This includes areas such as thermoelectric thin films, photoelectric thin films, and thermal and environmental barrier coatings. These technologies are used in waste heat recovery in the automotive and space industries, solar power generation, and organic light emitting diodes, and turbines in next generation power plants and clean aviation.

6 Enabling Science and Technology

It should be necessary to strengthen basic knowledge in different fields of science. Priorities for enabling science and technology are distributed in two main families and listed as follows (Fig. 1: Items 5.1.1–5.2.3):

6.1 Thermophysical Properties Metrology

Three scientific aspects (Fig. 1: Items 5.1.1–5.1.3) will be tackled: First the properties and methodologies of interest include transport properties, radiative properties, caloric properties, thermal analysis, and some thermodynamic properties. Then, the material states—solid, liquid, and gas—and also the equilibrium and transition phases as well as the types of material—bulk, advanced, and multifunctional—will be considered. Each particular case will be selected according to the triggers and the needed priorities. Finally, interfacial or multilayer systems will be studied. Due to the vastness of the scientific field, priorities will be optimized in agreement with the current European metrology programme for innovation and research in progress.

6.2 Advanced Metrology for Thermophysical Properties

The scientific research described in the previous paragraph will be upstream guided in this present section by the need (Fig. 1: Items 5.2.1–5.2.3) to work on advanced metrology dedicated to the thermophysical properties of materials, answering the emergence of newly advanced materials. The objective is to better manage the fundamental understanding of heat and mass transfer at multiple scales. Advances in technology are increasingly dependent on micro- and nano-scale engineering, from simple thin-film coatings to highly complex nano-structured systems. For many such applications, the thermal performance is an essential component. However, thermal transport at these length scales is poorly understood due to the substantial challenge of measuring heat transfer with sufficient resolution. Furthermore, it is noticed that the advance of thermal measurements at high temperatures requires newly developed advanced ceramics, composites, alloys, and specific temperature sensors or instrumentation. A fundamental understanding of heat transfer in highly complex or porous materials (bulk material) and at their boundaries (interfaces) is vital when comparing thermophysical properties data measured using different measurement techniques.

7 Conclusions

The outcomes of this roadmapping exercise were to identify the current state-of-the-art and future developments in the thermophysical properties metrology field. To achieve all the identified objectives would require the collaboration and also cooperation in the wider international scientific community. It is anticipated that this roadmap will become a useful tool for demonstrating need and rationale for further research in the field of thermophysical properties metrology development and metrology infrastructure, wherever justifications are needed at both national and international levels. These proposals on the direction of future thermophysical properties metrology will, if implemented, address the issues.

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References

1. J. Bojkovski, J. Fischer, G. Machin, F. Pavese, A. Peruzzi, E. Renaot, E. Tegeler, Int. J. Thermophys. **30**, 1 (2009)
2. Horizon 2020. http://ec.europa.eu/programmes/horizon2020. Accessed 22 June 2012
3. Horizon 2020 - The Framework Programme for Research and Innovation, COM (2011) 808 final, Brussels. http://ec.europa.eu/research/horizon2020/pdf/proposals/com(2011)_808_final.pdf. Accessed 30 November 2011
4. European Commission, Commission Staff Working Paper - Executive Summary of the Impact Assessment, Horizon 2020 - The Framework Programme for Research and Innovation, SEC (2011) 1428 final, p. 2, Brussels. http://ec.europa.eu/research/horizon2020/pdf/proposals/horizon_2020_impact_assessment_report_executive_summary.pdf. Accessed 30 November 2011
5. European Commission, Commission Staff Working Paper - Impact Assessment, Horizon 2020 - The Framework Programme for Research and Innovation, SEC 1427 final, pp. 35, Brussels (2011). http://ec.europa.eu/research/horizon2020/pdf/proposals/horizon_2020_impact_assessment_report.pdf. Accessed 30 November 2011
6. European Metrology Research Programme-Outline 2008, Report (2008). Available at http://www.euramet.org/index.php. Accessed 27 May 2010
7. J.-R. Filtz, B. Hay, J. Hameury, Int. J. Thermophys. **32**, 2741 (2011)
8. D. Salmon, R. Tye, N. Lockmuller, Meas. Sci. Technol. **20**, 015101 (2009)
9. D. Salmon, R. Tye, N. Lockmuller, Meas. Sci. Technol. **20**, 015102 (2009)
10. JCGM 100:2008 (GUM 1995 with minor corrections), Evaluation of Measurement Data—Guide to the Expression of Uncertainty in Measurement (2008)