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ITS10 Conference Digest

Tenth International Temperature Symposium
Anaheim, CA USA
April 3-7, 2023

Christopher Meyer
Editor, ITS10 Conference Proceedings

Kathryn Miller
Editor, ITS10 Conference Digest

Weston L Tew
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Howard Yoon
Vice Chair, International Program Committee

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Abstract

The 10th International Temperature Symposium (ITS10) was held in Anaheim California on April 3rd to 7th, 2023. More than 180 abstracts were received and accepted and 159 of those were presented at the symposium. This document is a record of the symposium program as it occurred. The program consisted of 5 plenary sessions, 28 parallel sessions, 3 poster sessions and 3 introductory workshop courses. A total of 15 invited speakers were included in the program whose expertise and presentation subject matter covered a wide range of topics within the overarching theme of: “Temperature, humidity and trace moisture, their measurement and control in science and industry”.

Keywords

Calibration Methods, Cryogenic Thermometry, Digital Transformation, Electronic and Noise Thermometry, Emissivity, Environmental and Climate Thermometry, Fixed Points, Harsh Environment Thermometry, Humidity and Moisture Metrology, Instrumentation and Data Analysis, International Comparisons, Luminescence Thermometry, Medical and Biological Thermometry, Nuclear Environments, Photonic Thermometry, Platinum Resistance Thermometry, Radiation Thermometry, Resistance Thermometry, Space and Astrophysics Thermometry, Temperature Control, Temperature Scales, Thermal Imaging, Thermocouple Thermometry, Thermodynamic Thermometry, Uncertainties and Statistics.

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Foreword

Introduction from Dr. Laurie E. Locascio. Opening Plenary Session of the 10th International Temperature Symposium. Tuesday April 4, 2023, Anaheim California.

Good morning and welcome to the 10th International Temperature Symposium. I'm Laurie Locascio, Director of the National Institute of Standards and Technology and I would like to wish all of you there in Anaheim a productive week at ITS10. Now, as many of know, this 10th meeting marks a significant milestone in the history of the Temperature Symposia. Just over 100 years ago, in 1919, the National Bureau of Standards, as it was known then, helped to organize the Symposium on Pyrometry. And it was the first in what would become this important series of gatherings. Now, while the name has changed a few times over the years, the central theme and the mission of these symposia remain the same, with their focus on temperature, its measurement and control in science and industry.

And while the symposia have been held at irregular intervals of between 7 and 20 years, they have remained consistent in addressing a broad scope of topics related to the scientific and technical progress in the field of temperature measurement. Now, looking back over the years, I'm struck by the dedication and vision of the scientists and engineers who took on the daunting task of organizing these symposia. That very first symposium took place in the shadow of a global pandemic, just as this one does today. And you should all be proud of how you have managed to continue this tradition through many years and many challenging world events. Now, as we look forward, we see many technical challenges ahead and an increasingly kind of connected and complex interplay of world economies.

Temperature measurement will continue to play an important role in research, in trade and in commerce. And these symposia are vital to ensure the right people come together to address challenges and drive advances in science and technology. So I'd like to thank you all for continuing this very important tradition. Good luck and best wishes for a successful symposium.

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ITS10 International Program Committee – Full Roster

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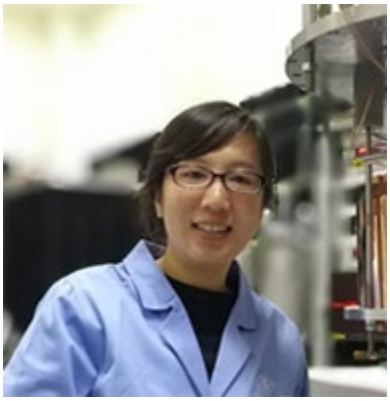
Jintao Zhang, National Institute of Metrology, China

Invited Speakers

Dr. Hisashi Abe received his PhD degree in physics from Kanazawa University. After working at the National Institute for Advanced Interdisciplinary Research and the National Institute for Resources and Environment as a postdoctoral fellow, he joined the National Metrology Institute of Japan (NMIJ/AIST) in 2001 and has been working on humidity standards. He was a visiting researcher at Nicolaus Copernicus University in 2009. He is the vice chair of the working group for humidity (WG-Hu) in the Consultative Committee of Thermometry (CCT), chair of the Technical Committee of Thermometry (TCT) in the Asia Pacific Metrology Programme (APMP), and the leader of the working group for humidity in the APMP TCT. His current research interest is the development of reliable techniques for humidity measurement using laser spectroscopy.

Dr. Thinh Q. Bui received his PhD in chemical physics at Caltech (Pasadena, CA) in 2016 and was an NRC post-doctoral fellow at JILA/University of Colorado, Boulder until 2019 when he started his career at NIST in Gaithersburg, MD. Prior to NIST, his training was on fundamental collision dynamics, interactions, and structure of atoms and molecules, relying on optical methods (ultrafast lasers, frequency combs) for spectroscopic interrogation. At NIST, his work transitioned to the development of magnetic imaging instrumentation and characterization of magnetic nanoparticles for sensing and thermometry. His other interests at NIST include the development of photonic sensors for pressure and temperature, and calibrated radiometric sources as an artificial star for astronomy/astrophysics in collaboration with NASA Goddard.

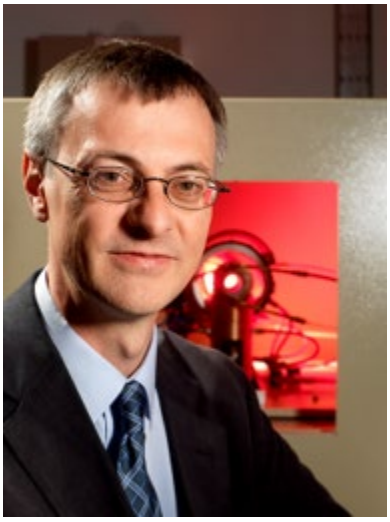
An expert in cold atom sensing and precision measurement, **Stephen Eckel** graduated from Yale University with a Ph.D. in Physics in 2012. His graduate work focused on two different precision measurement searches for the electron's electric dipole moment. After completing his Ph.D., he moved to the National Institute of Standard and Technology's (NIST) Joint Quantum Institute, where he was a National Research Council Postdoctoral Fellow working on inertial sensing using ring-shaped Bose-Einstein condensates. In 2016, he transitioned into the Thermodynamic Metrology Group at NIST and helped start the new cold atom vacuum standard project. His current research focuses on using atoms and molecules as sensors for both pressure and temperature. He has co-authored over fifty papers and has six patents.



Dr. XiaoJuan Feng received PhD and bachelor's degrees from the Department of Thermal Engineering in Tsinghua University in 2010 and 2005, respectively. She joined the National Institute of Metrology (NIM) in July 2010 and is now the group leader of NIM's contact thermometry group. She has worked on cylindrical acoustic gas thermometry for the determination of the Boltzmann constant, thermodynamic temperature, temperature measurement techniques using nitrogen-vacancy centers in diamond, and cryogenic fixed points. She was a guest researcher at National Institute of Standards and Technology (NIST) in Gaithersburg, MD, from Feb. 2012 to Jan. 2013 and from March to May 2017 in collaboration with Dr. Michael Moldover and Dr. Keith Gillis.

Dr. Christof Gaiser received his diploma degree in physics at the Humboldt-Universität zu Berlin in the field of optical and electrical properties of semiconductors in 2003. Since 2004 he is with the Physikalisch-Technische Bundesanstalt (PTB) in Berlin and received his doctor degree in 2008 in physics in the field of thermophysical properties of helium at low temperatures and gas thermometry. Since 2007 he dedicated his work to the determination of the Boltzmann constant as basis for redefining the SI base unit kelvin. He managed the international "Boltzmann project" which was the starting point for worldwide experiments leading to the successful redefinition of the kelvin in 2019. He is the head of the PTB working group "Cryo-and Primary Thermometry" and the chairman of the CCT working group on contact thermometry.

Dr. Kenneth T V Grattan graduated in Physics from The Queen's University of Belfast with a BSc, followed by a PhD in Laser Physics in the use of laser-probe techniques for measurements on potential new dye laser systems. He became a Research Fellow at the Imperial College of Science and Technology where he worked on advanced photolytic drivers for novel laser systems. Subsequently, he joined City, University of London, was appointed Professor of Measurement and Instrumentation and Head of the Department of Electrical, Electronic and Information Engineering. His research interests are wide and include the use of fiber optic and optical systems in the measurement of a range of physical and chemical parameters for industrial applications. He was awarded a DSc from City University London for his work in sensor systems. He was President of the Institute of Measurement & Control in 2000. He was awarded the Calendar Medal and the Honeywell Prize of the Institute of Measurement and Control and the Applied Optics Divisional Prize of the Institute of Physics in 2010 and is now Director of City's Institute of Sensors & Instrumentation. He was elected a Fellow of the Royal Academy of Engineering in 2008 and holds a Royal Academy of Engineering Research Chair in Scientific Instrumentation at City. He was appointed an Officer of the Order of the British Empire (OBE) in 2018. He is the author of over 700 publications in major international Journals and a similar number at key Conferences worldwide and is the co-editor of a five-volume topical series on Optical Fibre Sensor Technology.



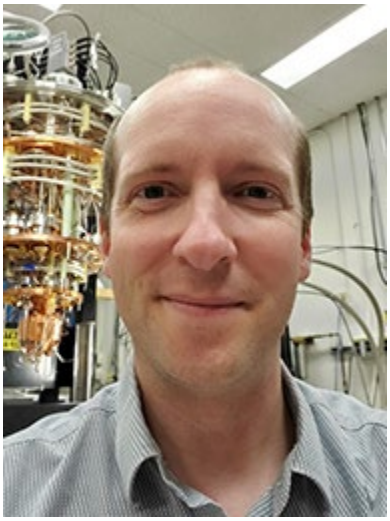
Dr. Graham Machin FREng, BSc (Hons), DPhil (Oxon), DSc, CPhys, CEng, FInstP, FIPEM, FInstMC is an NPL Senior Fellow. He has more than 30 years' thermometry research experience and has published more than 250 papers and given numerous keynote addresses. He is visiting Professor at Strathclyde, Surrey, and Birmingham Universities and Colaborador Honorifico at Valladolid University in Spain. Dr. Machin represents the UK on the Consultative Committee of Thermometry (CCT), chairs the CCT working group for Noncontact thermometry and led the recent update of the 10-year CCT Strategy. He was President of the UK Institute of Measurement and Control (2018-2019), chair of the Euramet Technical Committee for Thermometry (2014-2018), and served on the UK EPSRC Physical Sciences Strategic Advisory Team (2014-2017). Dr. Graham has received the Callendar medal from the Institute of Measurement & Control (InstMC) for "outstanding contributions to temperature measurement" and in 2019 was elected Honorary Scientist of the Chinese Academy of Sciences and Fellow of the Royal Academy of Engineering. In

2021 he was awarded the InstMC Harold Hartley medal for outstanding contributions to the technology of measurement and control. He is currently director of the 21-partner Euramet "Realising the redefined kelvin" project, leads NPL's metrology activity in nuclear decommissioning, and chairs the "UK Body Temperature Measurement Group."

Dr. Jonathan Pearce leads the contact thermometry technical area of the Temperature & Humidity Group at the UK's National Physical Laboratory. He is also Head of Science for the Thermal and Radiometric Metrology department. He has published over 160 articles on measurement issues. Research highlights include the development of new thermocouples and high temperature fixed points for contact thermometry, characterising uncertainty contributions of standard platinum resistance thermometry and fixed points used as temperature standards, introducing new techniques for overcoming calibration drift including self-validating sensors, low-drift thermometry, supporting the development of practical primary Johnson noise thermometry, and developing digital approaches to temperature metrology. He is the UK representative on the EURAMET Technical Committee for Thermometry (TC-T) and represents the UK in various BIPM Consultative Committee for Thermometry (CCT) and EURAMET TC-T working groups. He serves on standards committees including BSI and IEC. He is a Fellow of the Institute of Physics.

Dr. Sarah Purkey received her PhD in Oceanography from the University of Washington in 2013. She joined Scripps Institution of Oceanography, UC San Diego as an assistant professor in 2017. Her research is in large-scale observational physical oceanography with a focus on quantifying temperature, salinity, and circulation changes in the deep and abyssal ocean – those regions of the ocean below 2,000 m that are difficult to access with current technology. Her research has shown that the deep ocean has warmed over the past three decades, and this previously unaccounted for deep warming contributes significantly to ocean heat content and sea level rise. Much of her current research is focused on advancing ocean observations, specifically through her work on Argo technology, a global array of autonomous profiling ocean floats that monitor the ocean's heat, freshwater, and biogeochemistry.

Dr. David M. Romps is a Professor of Climate Physics in the Department of Earth and Planetary Science at UC Berkeley and a Faculty Scientist in the Climate and Ecosystem Sciences Division at Lawrence Berkeley National Laboratory. He studies the fundamental physics of climate and educates students and the public about global warming. Dr. Romps received a BS in math and a BS/MS in physics from Yale University and a PhD in physics from Harvard University. Motivated by concerns about climate change, he left the field of string theory to work on climate policy at the Woods Hole Research Center and on atmospheric dynamics at Harvard's Center for the Environment. He then joined the faculty at UC Berkeley and currently teaches the popular course *Introduction to Climate Change*.



Dr. Patrick Rourke received his PhD from the University of Toronto and held a Postdoctoral Fellowship at the University of Bristol before joining the National Research Council Canada in 2012 as an NRC Metrology Research Officer in the Thermometry & Radiometry team. His research focuses are primary thermometry and temperature scales, including recent work on the reproducibility of the International Temperature Scale of 1990, alternatives to mercury fixed points, refractive-index gas metrology, and acoustic gas thermometry. Dr. Rourke represents Canada internationally as national delegate to the CIPM Consultative Committee for Thermometry (CCT), member of the CCT Working Group for Contact Thermometry, and the inaugural chairperson of the CCT Task Group on Digitalization.

Dr. Steffen Rudtsch has a university degree in physics and a PhD in thermophysics. After 12 years as the head of the thermophysical properties laboratory at the Brandenburg Technical University at Cottbus he joined Physikalisch-Technische Bundesanstalt (PTB) in 1999. He worked as a guest researcher at NIST (USA) and NIM (China) and is now head of the Temperature department at PTB. He serves as chair of the EURAMET Technical Committee for Thermometry, PTB representative on the BIPM Consultative Committee for Thermometry (CCT), and member and chair of several working groups and committees within CCT, EURAMET, COOMET, IMEKO, DIN, DKE, DKD, and DAkkS. Dr. Rudtsch has an extensive list of scientific publications and has made several contributions to scientific books on thermometry and thermophysical property measurements. He has given numerous

lectures around the world and received the Netzsch Award of the European Thermophysical Properties Conference in 1999.

Dr. Mohamed Sadli is the head of the temperature division of LNE and oversees the research activities in thermometry at the joint laboratory for metrology LNE-Cnam. After a Master's Degree in Solid-State Physics, he earned a PhD degree in Metrology at Cnam in 1997, focusing on the study of the applications of pressure-controlled heat-pipes in thermometry. He joined the radiation thermometry group of LNE-Cnam after the PhD to lead the research and calibration activities in this area. His current research activities are primary thermometry, high-temperature fixed points, radiation thermometry, and thermocouples. He authored or co-authored more than 150 research articles and communications. He represents France at the CCT, EURAMET TC-T and IMEKO TC-12. He contributes to the activities of CCT "Non-Contact Thermometry" working group, leads the EURAMET TC-T "Strategy" working group as well as the task group devoted to a new CCT guide on industrial radiation thermometry. He coordinates the high-temperature research in the European joint research project Real-K.

Dr. Michele Scervini has been involved in thermocouple research since 2007, when he started a PhD at the University of Cambridge in the Department of Materials Science and Metallurgy. His PhD work focused on materials for thermocouples, in particular on the relationship between the drift of mineral insulated metal sheathed thermocouples and the metallurgical modifications occurring at high temperatures in these sensors. At the end of his PhD he devised a new concept, the dual wall thermocouple, to mitigate the drift of mineral insulated sheathed thermocouples. He continued to work in Cambridge as a research scientist to first demonstrate the validity of the new concept and measure its performance, characterised by low drift, and then to further develop the technology. His work has been funded through several grants from the European community (i.e. HEATTOP, METROFISSION, STARGATE, EMPRESS, EMPRESS2) and to a lesser extent from UK governmental funding (i.e. ALPHET). Throughout his work he has collaborated with several companies and research institutes both in Europe and USA. Before his PhD he received in 2004 a Master in Materials Engineering from the Politecnico di Torino and worked in Italy for General Electric in the gas turbine industry from 2004 till 2006. He started working in 2018 for ISOMIL GmbH, a mineral insulated cable manufacturer based in

Germany, while continuing to undertake his research in Cambridge. At the end of 2021 he left academia to relocate to Germany and today he continues his work on thermocouples in industry at ISOMIL GmbH.

Following an MA in Mathematics from Cambridge University, an MSc in Mathematical Modelling and Numerical Analysis from Oxford University and four years working in industry, **Louise Wright** joined the National Physical Laboratory in 1999. Her main area of expertise is in numerical simulation of measurement experiments, and her current interests include digital twins and virtual testing. She is NPL's Head of Digital Metrology, with responsibility for championing digital approaches across the scientific areas in the laboratory and enabling technical knowledge of digitalisation processes to be shared between different areas of measurement. She currently chairs the EURAMET working group on Metrology for Digitalisation (M4D) and the NAFEMS Computational Structural Mechanics Working Group.

ITS10 Scholarship Recipients

From the very beginning of the organizing process for the 10th International Temperature Symposium, the members of the organizing committee felt strongly that we needed to offer travel and registration assistance to participants from under-resourced countries within our regional metrology organization, the Inter-American Metrology System (SIM). We recognized the unique opportunity that the ITS10 offered for these participants to listen to and interact with technical experts from around the world in the field of temperature and humidity. Scholarship recipients were selected by their National Measurement Institutes. With support from Isotech North America and SIM, they were awarded scholarships consisting of full registration fees and all travel expenses. We are proud to continue a tradition which started in ITS9 and hope that this continues in future ITS symposia.

Name	NMI	Country
Bruno Lozano	INMETRO	Brazil
Billy Quispe	INACAL	Peru
Andres Jhovanny Bohorquez Garzon	INM	Colombia
Francis Hamilton	TTBS	Trinidad and Tobago
Javier Garcia Skabar	INRI	Argentina
Alberto Bedredin Velasquez Lopez	SDE	Honduras
Hamlet Herrera	INDOCAL	Dominican Republic

Acknowledgements

We wish to thank the members of the Measurement Science Conference Board of Directors for making the ITS10 possible. Karen Jackson, Chair; Tim Mason, President; Dawn Cross, Vice President; John Bowman; Mike Schwartz; and Miguel Cerezo. We are likewise grateful to the MSC volunteer staff for their essential support roles to the ITS10, including Cindy Becker, Tama Sturgeon, and Ralph Whittington. We are particularly grateful to Herb Dwyer, our Organizing Committee Chair, for his critical leadership role.

We would like to thank Magdalena Navarro of the NIST International and Academic Affairs Office for special assistance and support. We also wish to thank Jennifer Huergo and her staff at the NIST Public Affairs Office for their special contributions to the Symposium's centenary. Jacob Ricker of the NIST Sensor Science Division provided logistical support in his role as MSC Liaison. James Olthoff, the NIST Chief Metrologist, provided key leadership in international affairs coordination.

We would also like to thank the members of the ITS10 International Program Committee for their assistance in promoting and developing the content for the Symposium program. In particular, we would like to acknowledge the vital contributions of: Graham Machin of the National Physical Laboratory, UK; Jeffrey Eldridge of the NASA Glenn Research Center; and XiaoJuan Feng of the National Institute of Metrology, Beijing, China.

On behalf of the entire ITS10 leadership team, we would like to express our condolences to the MSC leadership and to the family and friends of Karen Jackson, who suddenly passed just days before the start of the event. Karen will be fondly remembered for her dedication and friendship and for her tireless efforts to bring the ITS10 to fruition.

Introduction

A Brief History of Temperature: The Symposia on Temperature turn 100 Years Old

Weston L Tew
Sensor Science Division, National Institute of Standards and Technology
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A Brief History of Temperature:

The Symposia on Temperature turn 100 Years Old

Weston L Tew
Sensor Science Division,
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Gaithersburg, MD USA

Introduction

In September of 1919 a 'Symposium on Pyrometry' was organized by the American Institute of Mining and Metallurgical Engineers (AIMME) in Chicago Illinois. The Symposium was held in cooperation with the US National Research Council (NRC) and the National Bureau of Standards (NBS). The field of pyrometry was generating a great amount of interest in both scientific and industrial communities and there were new methods of temperature measurement that had emerged as a result of research in this area.

The Chicago meeting was later viewed as a not only a symposium on pyrometry, but also on the larger subject of temperature measurement as an entire discipline in science and technology. In fact, this event became a catalyst for a series of major Symposia on Temperature, and each such conference came to be known as a 'Temperature Symposium', eventually adopting the name of 'International Temperature Symposium'. These symposia were repeated at somewhat irregular intervals of between 7 to 20 years with a broad scope of topics related to the measurement of temperature reviewing the scientific and technical progress in the field spanning the time since the preceding symposium. The proceedings from each of the Temperature Symposia since the original meeting of 1919 were published in print volumes and in digital form starting in 2002. Starting with Volume 1, published in 1939, these proceedings adopted the title "Temperature, Its Measurement and Control in Science and Industry" (TMCSI). The table below summarizes the evolving history of these symposia.

Throughout the history of these symposia, the management and scientific staff from the NBS and later NIST have been centrally involved in the planning, organization, presentation of papers, and eventually in the editing of their proceedings. Moreover, by reviewing the contents of those proceedings, we can trace the history of the scientific and technological progress in temperature measurement over the last century. This review will highlight these Symposia, including the people who organized and participated in them, as a chronology starting with the first event in 1919 and told from a NIST-centric perspective. I will preview the upcoming April 2023 event, the 10th International Temperature Symposium, in which the centenary will be recognized.

Table 1 A Summary of the Temperature Symposia and their Proceedings.

Year and Place	Conference Title	Proceedings Title	Publisher
1919, Chicago, IL	Symposium on Pyrometry	'Pyrometry, The Papers and Discussion of a Symposium on Pyrometry'	AIMME, New York, 1920
1939, New York, NY	Symposium on Temperature, Its Measurement and Control in Science and Industry	'Temperature, Its Measurement and Control in Science and Industry' (TMSCI), Fairchild, Hardy, Sosman, Wensel, Editors	Reinhold Publishing, New York, 1941
1954, Washington, DC	Third Symposium on Temperature, Its Measurement and Control in Science and Industry	TMCSI Vol 2, Hugh C Wolfe, Editor.	Reinhold Publishing, New York, 1955
1961, Columbus OH	Fourth Symposium on Temperature	TMCSI Vol 3, Charles M Herzfeld, Editor-in-Chief	Reinhold Publishing, New York, 1962-63
1971, Washington, DC	Fifth Symposium on Temperature	TMCSI Vol 4, Harmon H Plumb, Editor-in-Chief	Instrument Society of America, 1972
1982, Washington, DC	Sixth International Temperature Symposium	TMCSI Vol 5, James F Schooley, Editor-in-Chief	American Institute of Physics, 1982
1992, Toronto, Canada	Seventh International Temperature Symposium (ITS7)	TMCSI Vol 6, James F Schooley, Editor-in-Chief	American Institute of Physics, 1992
2002, Chicago, IL	Eighth International Temperature Symposium (ITS8)	TMCSI Vol 7, Dean C Ripple, Editor-in-Chief	American Institute of Physics, 2003
2012, Anaheim, CA	Ninth International Temperature Symposium (ITS9)	TMCSI Vol 8, Christopher Meyer, Editor-in-Chief	American Institute of Physics, 2013
2023, Anaheim, CA	10th International Temperature Symposium (ITS10)	TMCSI Vol 9, Christopher Meyer, Editor-in-Chief	American Institute of Physics, Date TBD

Symposium on Pyrometry, Chicago 1919

Despite the differing name, the 1919 Chicago Symposium was later regarded as the first Symposium on Temperature held in the western hemisphere. Much of the organization and planning for the 1919 Symposium was initiated by the Pyrometer Committee of the US NRC. The Chairman of this committee was George K Burgess, who was then the Chief of the Metallurgy Division of the NBS. Burgess would go on to become the second Director of the NBS, serving in that capacity from 1923 until his sudden death in 1932.

This meeting was held at the end of a great global pandemic since the infamous 1918 influenza pandemic had persisted into the spring of that year. This fact probably limited the attendance to

less than 100 participants. This was also a purely ‘national’ rather than international conference. All of the authors, and likely all of the attendees, were Americans.

The opening plenary lecture and first paper of the proceedings was an essay titled ‘Temperature', by Joseph S. Ames of Johns Hopkins University (JHU). Ames discussed the fundamental physics concerning temperature including the concept of ‘absolute zero’, as it had been conceived by Thompson (aka Lord Kelvin). Ames would later go on to become provost and then president of JHU, serving in that capacity until 1935. He was also a founding member of the advisory committee that later became the National Aeronautics and Space Administration (NASA).

George K Burgess, Second Director of the NBS and Chair of the Committee that organized the Symposium on Pyrometry held in 1919.

At the time of this symposium, the term ‘pyrometer’ was used to describe any instrument designed to determine elevated temperatures, which included both optical and thermoelectric instruments. The term ‘thermometer’ was mostly reserved for mercury-in-glass (MIG) instruments (‘mercurial thermometers’), whose practical upper limit was normally about 316 °C. Some specialized MIGs were constructed with sealed pressurized capillaries to suppress boiling of the Hg and those types could be used up to a limit near 540 °C. Hence, the field of pyrometry at that time was mainly focused on the measurement of temperatures above that limit. The increased interest in pyrometry was being driven largely by metallurgy and the iron and steel industry in particular. Better methods of temperature measurement were needed to improve the quality of forged metals and in steel production.

Temperatures were often reported in both degrees centigrade (°C) and degrees Fahrenheit (°F), with Fahrenheit being more commonly used in US industry. The only official international temperature scale in 1919 was the so-called ‘Normal Hydrogen Scale’ (NHS) of the International Bureau of Weights and Measures (BIPM). The NHS was based on a gas thermometer and defined between the ice melting point and the normal boiling point of water, and was therefore of limited utility with a range confined to just 0 °C to 100 °C. The NHS was disseminated to National Laboratories around the world via “primary standard mercurial thermometers made of French hard glass”. Determining the temperature of any observed phenomena above 100 °C involved a considerable amount of effort to provide both a laboratory scale and suitable temperature reference within the range of the NHS. But the leading National Laboratories of the time (The Physikalisch-Technische Reichsanstalt at Charlottenburg, Germany; the National Physical Laboratory at Teddington, England, and the NBS in Washington) were already contemplating setting up a new international temperature scale to extend the range of the NHS. These plans had already begun in 1912, but were interrupted during the period of World War I. The 1919 meeting was the first opportunity since the end of the war to allow this planning to resume.

The proceedings were published by the AIMME in 1920, titled as “Pyrometry, The Papers and Discussion of a Symposium on Pyrometry”[1]. Despite having the status of being the first Symposium on Temperature, these proceedings were never officially counted into the TMSCI series, resulting in a confusing offset between the indexing of the Symposia (‘*n*’) and of their associated Proceedings (*n*-1, as if the 1920 Proceedings were regarded as ‘Volume 0’). These proceedings were , in effect, somehow ‘lost’ or forgotten when the organizers of the 3rd Symposium decided the indexing convention in 1954. The NIST Library has a bound original

copy of this Volume 0 and there is a digitized public-domain version available from the Hathi Trust[2]. The editors were presumably taken from the staff working at the New York City office of the AIMME, but were unnamed in the as-published volume. There were sixty articles included in the 680 pages of the volume, not including the index and some advertisements. Twenty of those articles were contributions from the staff of NBS.

Symposium on Temperature, New York, 1939

Henry T Wensel, NBS.
Credit: AIP

The 'Symposium on Temperature – Its Measurement and Control in Science and Industry' was held in New York City during the 2nd ,3rd, and 4th of November of 1939. An announcement for the Symposium that appeared in the October edition of the Journal of Applied Physics [3] listed some 72 papers to be presented at the Symposium. It had been twenty years since the Chicago Symposium, and interest in the subject of temperature measurement had greatly increased as had the importance to many new industries. The organization for this symposium was led by the American Institute of Physics (AIP). John T Tate, Chairman of the AIP Governing Board, had formed a Symposium Advisory Committee from various leaders from US industry and academia. The actual organization was performed by a separate 'Symposium Committee', led by Henry T. Wensel, then Chief of the Pyrometry Section of the NBS in Washington DC. Wensel was one of four editors assigned to edit the proceedings and also authored the first paper in the Symposium, titled 'Temperature',[4] following the precedent begun by Ames 20 years prior. Other notable NBS contributors were Ferdinand ('Brick') Brickwedde, E. F. Mueller, Harold ('Stimmie') Stimson, Nathan Osborne and Edward Wichers, among others. Lyman J Briggs, then Director of NBS, presided over the opening plenary session. Some of these NBS scientists can be seen in the photograph shown below taken during the Symposium Dinner on November 3rd of that year.

The temperatures being reported at this time were on the scale of the 'International Temperature Scale' (ITS), which later became known as the ITS of 1927 (ITS-27)[5]. This was the consensus scale created by the International Committee on Weights and Measures (CIPM) in 1927. This scale replaced and extended the range of the NHS, with a range spanning from the liquid oxygen boiling point , assigned at -182.97 °C, to the gold melting point as assigned a value of 1063 °C. Higher temperatures were defined via an approximate expression for scaling the intensity of monochromatic light emitted by a black body radiator using optical pyrometers. ITS27 was the first modern temperature scale for practical use and broad application. Its adoption allowed a degree of uniformity in temperature measurement across all industries and global economies that was previously impossible.

During the 1930s there was a great deal of interest among physicists in determining the thermodynamic temperature of the ice melting point (IMP), or what was then referred to as the 'Kelvin Temperature' of the IMP. This was equivalent to establishing the value of absolute zero temperature on the so-called centigrade thermodynamic scale, where 0 °C was assigned to the IMP. Two papers were presented in the 1939 Symposium that reported analyses of archival data on the Joule-Thompson effect which could yield such temperature determinations. Roebuck and Murrell from the U. of Wisconsin calculated a value of 273.17 ± 0.02 as expressed in 'degrees

kelvin' or °K. James Beatie of the Massachusetts Institute of Technology (MIT) presented an in-depth thermodynamic analysis resulting in a value of 273.165 ± 0.015 in the same units. These and other similar determinations would be used to refine the thermodynamic basis for later versions of the ITS and to eventually define the unit for temperature in the International System (SI), the 'kelvin'.

The technology of temperature measurement had undergone a period of significant refinement and innovation during the 1930s. The technology of the platinum resistance thermometer had been brought to a state of maturity making it suitable for a defining standard on the new ITS27, allowing precise interpolation of temperature from -190 °C to + 660 °C. NBS physicists E F Mueller and C H Meyers were key contributors in the efforts to perfect the necessary techniques and methods.

At higher temperatures, the field of optical pyrometry was likewise undergoing rapid advancement. The ocular methods employing instruments with telescopic lens arrangements for comparison of internal and external sources, known as the 'disappearing filament pyrometer' were being perfected. Many new pyrometers were developed in the 1930s using vacuum-tube rectifiers as photocells which replaced the human eye as the detector. These included the so-called 'two-color' optical pyrometers in which the radiance was split into red- and green-filtered components for measurement of grey-body temperatures with unknown emissivity. A new type of detector was just emerging, however, in which a so-called 'blocking-layer' photocell was made from a selenium coating over a metal base with a thin film of gold on top to form a rudimentary solid-state rectifier.

The AIP sponsored dinner during the (2nd) Symposium on Temperature held at the Hotel Pennsylvania, November 3, 1939, in New York, New York. (AIP). Approximately 150 people can be seen in the photograph. NBS staff are likely about 20 % of those pictured. Harold Stimson can be seen seated at the front left table facing the camera. Wensel is seen at the third left-hand-side table back from there. Ferdinand Brickwedde can be seen at the second table back on the right-hand side looking over his left shoulder to the camera. Credit: AIP Digital Archives, Neils Bohr Library, Emilio Segrè Visual Archives. https://repository.aip.org/islandora/object/nbla%3A289633

The proceedings, "Temperature, its Measurement and Control in Science and Industry", were published in 1941 by Reinhold Publishing of New York City.[6] The single bound volume contained 126 papers in 1,292 pages, not including the numerous appendices and indices. About half of these papers were focused on fundamental aspects of temperature, scales, thermodynamics, and other basic scientific investigations. Twenty of those papers focused on bio-medical thermometry alone. The balance of the proceedings concerned a wide range of industrial applications including steam turbines, oil production, steel production, refrigeration, concrete and ceramics. The NBS staff contributed a total of 14 papers overall. This was again a mostly American Symposium, with only five papers from authors with affiliations from outside of the USA. The volume was highly successful from a publishing standpoint and proved to be a widely used reference for scientists and engineers, functioning much like a technical handbook. Reinhold issued at least 7 printings of the book, through 1958.

3rd Symposium on Temperature, Washington DC, 1954

The 'Third Symposium on Temperature – Its Measurement and Control in Science and Industry' was held in Washington DC in October of 1954. This was a smaller conference organized again by the AIP and the NBS, but with US Army Office of Ordinance Research providing additional support. In contrast to the 1939 Symposium, the 3rd Symposium in 1954 was more academic in focus. The emphasis was on the fundamental physics of temperature, temperature scales, and its measurement in both naturally occurring and anthropogenic processes. Hence, the 'Industry' component that was featured in the 1939 Symposium was mostly absent.

The organizing committee (aka the 'General Committee') for the 3rd Symposium on Temperature was Chaired by Allen V Astin, then Director of the NBS in Washington DC. The planning stage for the Symposium would have overlapped with the tumult of 1953 in which Astin was forced to resign his position as Director by the US Secretary of Commerce stemming from a controversy surrounding the commercial battery additive known as 'AD-X2'. Astin was later reinstated after five months of public uproar and congressional testimony. [7]

Allen V. Astin, director NBS, 1951 to 1969. Credit: NIST

The Symposium's General Committee and Program Committee were composed of notable scientists from both Government and University institutes working in the US at that time. Director Astin was joined by Ferdinand Brickwedde and William Wildhack of the NBS. Joseph E Mayer, a well-known professor of chemistry, was an author in statistical field theory, and husband to Nobel Laureate Maria Goeppert Mayer. Herbert B Callen was a well-known physicist and theorist in thermodynamics and statistical mechanics, who along with Theodore Welton had developed the foundational 'Fluctuation-Dissipation Theorem' in 1951.[8] Other committee members included: the research director at the Office of Naval Research, Shirleigh Silverman; the professor and text book author Mark W Zemansky; and the Austrian-American physicist Karl F. Herzfeld.

The 3rd Symposium consisted of just 26 presentations over three days, 24 of which were later published in the Proceedings. Five of those papers were contributions from NBS scientists. The Symposium was for the first time significantly international in its character, with 8 of the 26

speakers from outside of the US. Many of the published papers were in-depth treatises on the temperatures associated with unusual physical systems, thermodynamics and primary thermometry, temperature scales, techniques and methods for temperature measurement. These various topics spanned the range of temperatures from 0.003 K utilizing the magnetic susceptibility of paramagnetic salts, to that of stellar surface temperatures exceeding 1 MK, and to the temperatures associated with nuclear weapon detonations reaching 50 MK. The proceedings from the 3rd Symposium were edited by Hugh C Wolfe on behalf of the AIP, and published in 1955 by Reinhold [9]. Wolfe was chair of the physics department at Cooper Union School of Engineering and later became the first 'Director of Publications' for the AIP in 1960. Wolfe also authored the first paper in the Symposium, titled 'The Temperature Concept', a review of the fundamental thermodynamics that carried on a tradition established from the two earlier symposia. In contrast to the practical 'Handbook' nature of the 1941 proceedings (volume 1), the volume 2 was more similar to an academic textbook.

A new international temperature scale (ITS-48) had been established in 1948, being practically identical to the ITS-27 below 630.5 °C, but altered in definition above that point. This involved changing the definition of temperature from one based on Wien's Law to one based on Planck's Law. The ITS-48 also adopted new terminology, in that those temperatures specified relative to the Ice Melting Point (IMP) be designated as 'degrees Celsius' only, and to discontinue the old name of 'centigrade', both being formerly in use with the unit notation '°C'.

That same year, 1954, the Comité Consultatif of the CIPM had adopted a 'thermodynamic Kelvin scale' where the temperature of the triple point of water was fixed at 273.16 K. This temperature was chosen after a value of 273.15 K (or 0.01 °C) was adopted for the IMP, given that the difference of 0.010 K between the IMP and the triple point of water had been precisely determined [10] and that the latest available data from absolute gas thermometry , together with published corrections, all agreed at the IMP to within about 0.001 K. This produced a dichotomy in temperature metrology, having one temperature scale derived from first principles and another being a collection of empirical definitions and rules for practical interpolation. In practice, it was a distinction without a difference, since any numerical differences were unresolvable given the available measurement technologies of the day.

Perhaps the most surprising development in the history of temperature measurement had occurred just a few years prior to the third Symposium. It was discovered in 1951 that negative absolute temperatures could occur in systems of nuclear spins. Norman Ramsey and his research associates at Harvard University were studying the nuclear magnetic interactions associated with the nuclei in LiF crystals where the energy of the system is both quantized and bounded, leading to negative absolute temperatures and some very counterintuitive thermodynamic characteristics.[11] At that time, both the concept and the results leading to the observation of negative absolute temperatures were still somewhat controversial, or at least not widely understood. The subject was treated briefly but clearly during the 3rd Symposium and is found near the end of a paper authored by Sir Francis Simon of Oxford University, "The Concept of Temperature Near Absolute Zero".

4th Symposium on Temperature, Columbus OH, 1961

William A Wildhack, NBS, Credit: NIST

The 'Fourth Symposium on Temperature' was held in Columbus Ohio over five days in March of 1961. The fourth Symposium was sponsored by the AIP, the Instrument Society of America (ISA), and NBS. Two NBS scientists were most pivotal in the organization of the Symposium. First, there was William A Wildhack, who served as the Chair of the General Committee. Wildhack held many different leadership positions during his 34 year tenure at NBS, including Chief of the Office of Basic Instrumentation, Special Assistant to the Director, and Associate Director, Institute for Basic Standards. Second , there was Charles M. Herzfeld, then Chief of the Heat Division at NBS, who served as Chair of the Symposium's Program Committee and Editor-in-Chief of the Symposium Proceedings. Herzfeld would later go on to hold many other positions in both other Federal Agencies and in US private industry, including Director of Defense Research and Engineering at the Department of Defense under President George H. W. Bush. Ferdinand Brickwedde also served as an editor and on the Symposium's Program Committee, but at this point in time Brickwedde had left NBS and taken a faculty position at Pennsylvania State University.

The fourth Symposium was the largest of those yet held, judging from the number of papers found in the proceedings; approximately 250 papers were likely presented. This large number of papers necessitated dividing the proceedings into three parts, which were printed and bound as three separately bound volumes, (i.e. Volume 3, Part 1, Part 2, and Part 3).[12] Each of these partial publications were separately edited and printed by Reinhold in succession, with the final part 3 being issued in 1963. So in a sense the 4th Symposium on Temperature was actually three separate Symposia. The first being focused on 'Basic Concepts, Standards and Methods', the second on 'Applied Methods and Instruments', and the third and final part focusing on the role of temperature in 'Biology and Medicine'. The fourth Symposium had significant international contributions , with about 10 % of the papers being presented by authors from outside of the US.

The organizers of the Fourth Symposium had shortened the title by omitting the phrase 'its measurement and control….'. This phrase may have been considered too restrictive or perhaps too cumbersome. Nonetheless, the complete title as inherited from past Symposia was retained for the purposes of the Proceedings. While Reinhold held the original copyrights to those proceedings, other printings have been issued by the R E Krieger Publishing Company. Printing the entire volume 3 would have been a significant undertaking, requiring 2,624 pages when combined from all three parts. Taken together, this volume took the form of an 'encyclopedia of temperature', covering almost every related topic imaginable.

The opening lecture and first paper in Part 1 of the 4th Symposium was titled 'Temperature Concept for Systems in Equilibrium' presented by the well-known scientific author Robert Bruce Lindsay, following the established tradition for the Symposia. This was followed by a lecture on 'Thermodynamics and Statistical Mechanics at Negative Absolute Temperatures' given by Harvard physicist and future Nobel Laureate Norman Ramsey. Ramsey's lecture occurred on the 10th anniversary of the publication of his discovery.[11] The remaining 81 papers from Part 1 spanned topics from low temperature phenomena and scales down to about 1 mK in systems of nuclear spins to the temperatures of high-energy plasmas over 10^5 K, to those found in the Solar

Corona of > ≈2 MK. NBS authors contributed 19 of those papers, one of which was written by Ralph P Hudson. Hudson was a key member of a team of NBS scientists led by future NBS/NIST director Ernest ('Ernie') Ambler, who worked on nuclear orientation thermometry using the radioactive isotopes of cobalt. In 1956 the team had conducted a very difficult experiment in which they verified the violation of parity conservation in the beta decay of ^{60}Co as governed by the 'weak' nuclear force.[13] This and other experiments elsewhere led to the Nobel Prize in Physics being awarded to T D Lee and C N Yang who had predicted the effect.

The ITS-48 was still in use at the time of the 4th Symposium, but this ITS had itself undergone a revision to the text in 1960. In particular there was a need to revise certain sections which were in conflict with the recent adoption of the definition of the unit kelvin through the triple point of water being fixed at 273.16 K exact. In addition, recent research at the National Research Council of Canada had shown that the freezing point (FP) of zinc was superior in reproducibility to that of the sulfur boiling point as defined on the ITS-48. The scale as so revised became the International *Practical* Temperature Scale (IPTS) of 1948. The IPTS-48 incorporated the changes in a such a way as to not fundamentally alter the ITS-48 itself, but to amend the text to accommodate the scientific progress being made in the field of fixed point temperature standards. Other pure metal freezing points were likewise being refined to provide standard's level quality , such as those from high-purity samples of Cd, Pb, Sn, and In.

Other non-metal fixed points were being investigated as well, but in this case these were mostly at cryogenic temperatures that were below the lower limit of the ITS-48 of 90.18 K (the O_2 normal boiling point). In particular, the vapor-pressure temperature relationship for the ortho and para forms of hydrogen had to be established using any one of four different gas thermometer scales in use at the time for purposes of low temperature thermometry. The papers presenting results for these non-metal fixed points at the 4th Symposium had to therefore account for possible differences in these various thermodynamic temperature scales.

The second part of the 4th Symposium focused on the practical aspects of temperature measurement of primary concern to industry. Authors from a wide variety of industries contributed to the 103 papers that were published in Part 2. This was primarily thermoelectric thermometry using base-metal and noble-metal thermocouples, and pyrometry (more properly known as 'Radiation Thermometry') using a host of different technologies for optical and infrared detectors. Rapid technological progress was occurring in both of these areas, driven in part by the requirements associated with aerospace and space-launch systems development. An international 'space race' had begun just a few years before the Symposium took place and new technologies associated with liquid-fueled rocket engines and the associated cryogenic fuels and oxidizers required better thermometry at both extremes of hot and cold.

Thermocouples had been in use for decades, but the many factors affecting their reproducibility were still not completely understood. Moreover, the industrial specifications for alloy thermoelements and thermocouples were still tied to their chemical composition, and the data needed to switch to performance-based specifications were still lacking. Hence, thermocouple consensus standards would not be in place until about another 10 years or more into the future.

Pyrometers with spectral coverage into the infrared were being developed around this time, and solid state detector technologies were rapidly emerging to replace the more cumbersome vacuum tube designs and the 'thermal'-type detectors such as those made from thermopiles. Silicon-based diodes were under development which gave superior sensitivity into the red and near

infrared compared with selenium. Compound semiconductors were also coming into play, and detectors made from InSb were just becoming viable, allowing coverage into the mid-infrared. The performance of practical radiation thermometers vastly improved from innovations associated with these new detector materials. These and other features were highlighted in a paper given by Barber and Land of Land Pyrometers Ltd in England.

The third and final part of the 4th Symposium was primarily devoted to temperature measurements in biological systems and medicine. This was a remarkable volume in and of itself given the full scope of the subject matter and considerable depth of the 56 papers that were later published. Physiology, neurology, thermoregulation, sensation, heating and hypothermia were all treated in this partial Symposium. This part of the proceedings was edited by John D Hardy of the John B Peirce Laboratory, a research institute focusing on human physiology and affiliated with Yale University in New Haven, CT.

5th Symposium on Temperature, Washington DC, 1971

Ralph P. Hudson, NBS.
Credit: NIST

The 'Fifth Symposium on Temperature' was held in Washington DC over four days in June of 1971. The fifth Symposium was once again sponsored by the AIP, the ISA, and NBS. Once again two NBS scientists had teamed up to lead the organization of the Symposium. Ralph Hudson, then Chief of the NBS Heat Division, served as the Symposium General Chairman. His counterpart chairing the Program Committee was NBS staff scientist Harmon H Plumb, who also served as the editor in chief for the proceedings. The NBS scientific staff contributed approximately 10 % of the papers presented at the 5th Symposium.

The proceedings from the 5th Symposium were again given the traditional title of 'Temperature, Its Measurement and Control in Science and Industry' Volume 4. [14] A new publisher had been arranged for this volume, the ISA. This was another massive output of 2,383 pages in three parts, containing a total of 215 papers yielding another 'encyclopedia of temperature'. The distribution of topics between the three parts of the volume 4 could not, however, be made in the same way as was done for Volume 3. Part I contained 69 papers on Temperature Scales and Fixed Points, Radiation Thermometry, Acoustic Thermometry and Special Techniques; Part II contained 75 papers on Resistance and electronic thermometry, Magnetic Thermometry, Temperature Control and Calibration, and Bridge Instrumentation; part III contained 71 papers on thermoelectric thermometry, medical and biological thermometry, and Geophysical and Astrophysical Temperature Measurements. Approximately 30 % of the papers were presented by authors from outside of the USA, making the 5th Symposium by far the most international of those meetings yet held.

A new temperature scale had been just recently adopted and many of the papers presented in Part 1 concerned certain aspects of the new scale, the ITPS-68.[15] This scale involved major changes from the IPTS-48 and extended its range downward to a lower limit of 13.8 K. A series of five new non-metal fixed points were introduced below 90.18 K in order to support that extension. The sulfur boiling point as defined in the IPTS-48 was replaced by the Zn FP. The

normal boiling point (or ‘steam point’) of water was retained at 373.15 °C , but the Sn FP was added as a suitable alternative fixed point.

The new scale included adjustments in the definitions to bring the as-realized temperatures into close agreement to the thermodynamic scale as defined via the kelvin and as realized via primary gas thermometers. Yet the basic structure of the IPTS-68 was essentially the same as that of its predecessor scales, going back to the original ITS-27. This structure was established by matching the best available temperature interpolation standards to the most-suitable temperature ranges: a standard platinum resistance thermometer (SPRT) defining the lowest temperatures up 630.74 °C ; a Pt versus Pt-10 % Rh thermocouple defining an intermediate temperature range up to the Au FP (1064.43 °C); and pyrometers using a scaling relationship derived from the Planck Radiation Law for temperatures from that point upwards.

Like all of its predecessors, the IPTS-68 was a product of both science and international diplomacy, since it was adopted by an international consensus body, the CIPM. It was in some sense a compromise between the different viewpoints of the various members of the Consultative Committee on Thermometry (CCT) of the CIPM. These points were emphasized by Hugh Preston-Thomas of the NRC of Canada in his opening lecture for the 5th Symposium. Moreover, upon its adoption in 1968, it was still an abstraction, and not yet fully realized according to its definitions in any laboratory. So, its weaknesses and flaws were not fully understood until years after its adoption. This realization was becoming apparent by the time of the 5th Symposium, and various papers were presented that scrutinized certain aspects of the IPTS-68 in ways that were not available prior to 1968. For example, papers were presented on new primary thermometry methods using total radiation thermometers, noise thermometers and acoustic thermometers. In addition, Furukawa and Reilly of the NBS showed that precision heat capacity data could be used to examine the interpolation properties of the IPTS-68 and detect the presence of unphysical artifacts or deviations from thermodynamic temperatures.

Platinum resistance thermometers (PRTs) were being refined and perfected during the 1960s to provide higher temperature use, and also to use smaller diameter wire with higher chemical purities. This had an impact on the quality of both reference-grade platinum as used in standard PRTs (SPRTs), and also industrial-grade platinum as used in many commercial applications. This was evident from the dozen or so papers concerning PRTs and SPRTs presented at the 5th Symposium. While the meaning of ‘reference-grade’ Pt was clearly defined via the IPTS-68, this was not the case with the more common industrial grades. In fact, many different industrial PRT standards were emerging at the time, based on slightly different compositions, with slightly different temperature coefficients, and were in use in different industries and in different parts of the world. Greater harmonization for industrial PRTs would not be achieved for another decade to come.

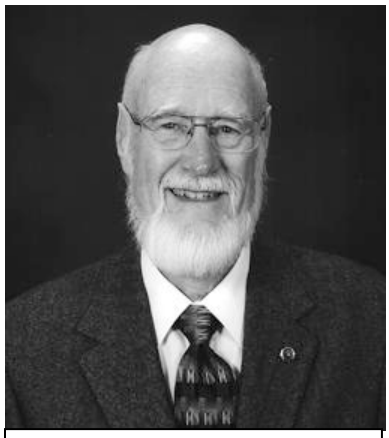
Thermoelectric thermometry was likewise advancing rapidly, and new refractory metal thermocouples based on W-Re alloys were now in place for use up to about 2300 °C. Reference tables were being developed for some of the most common noble-metal compositions and some base-metal combinations. Those efforts would soon form the basis of international consensus standards that would eventually become the common letter-type thermocouple reference standards that we rely on so frequently today. Some 42 papers were presented at the 5th Symposium on all aspects of thermocouple thermometry, with nine papers alone on specialized applications for nuclear environments.

Advances in electronics were also having an impact in temperature measurement. Digital electronics was still in its infancy, but clever analog methods were under development in AC resistance bridges and being applied to improve the precision and accuracy of resistance thermometry. But all these new instruments, five of which were described in papers from the 5th Symposium, still relied on manual operation by a skilled technician, which made all precision measurements of temperature a highly labor-intensive endeavor.

At low temperatures a new technology was emerging that could produce high-quality single-crystal germanium resistance thermometers. Four papers in the 5th symposium were presented on this topic. These could be doped with arsenic to produce n-type Ge with high sensitivities and manageable interpolation characteristics for a given temperature range, usually about 1.5 decade in temperature for a given level of doping. The Ge resistance thermometers would find uses as laboratory transfer standards at temperatures below 30 K for decades to come. But another innovation in low temperature thermometry was emerging about this same time. This was based on dilute magnetic alloys of Fe as a dopant in otherwise pure rhodium metal wire. A discovery of a new class of magnetic anomalies in dilute alloys proved useful for low temperature thermometry due to a linear temperature dependence being imparted to the resistivity at low temperatures by the iron impurity. Richard Rusby of the NPL in England presented his results for Rh-Fe alloys for the first time at the 5th Symposium. Both the n-type Ge and Rh-Fe resistance thermometer would later be adopted to commercialized laboratory thermometers.

In radiation thermometry, many new pyrometer instruments and methods continued being developed in the 1960s with improvements in sensitivity, accuracy and extended range into the infrared. Detector technology was advancing with more of the compound semiconductors being utilized. These included InAs and PbS types which were being applied as quantum detectors to instruments as alternatives to the better known Si and InSb types. Thermal detectors such as thermopiles and thermistor bolometers continued to be refined as well and remained the only real option for sensitivity beyond 7 mm wavelength. Some 26 papers on all aspects of radiation thermometry were presented at the 5th Symposium.

6th International Temperature Symposium, Washington DC, 1982



James F Schooley, NBS
Credit: NIST

For the 6th Symposium, the event returned to Washington DC, taking place March 15 to 18 of 1982. But this meeting would begin a new era with a new and more fitting name, the “Sixth International Temperature Symposium” (ITS6). Lawrence (‘Larry’) G Rubin of MIT’s Francis Bitter Laboratory was now taking the helm as the General Committee Chairman. At NBS, James F Schooley would step into the role as Program Committee chair, and his influence would endure for many decades into the future.

The ITS6 was sponsored by the ISA, AIP and the NBS. The ISA was responsible for the practical and financial arrangements and organized a co-located technology exhibition as part of the overall event. This first-of-its-kind exhibition brought in manufacturers of scientific equipment from private companies and augmented the practical impact of the Symposium. Schooley and his Symposium Program

Committee organized the technical program which attracted the largest international attendance yet, representing over half of the conference program with authors from 18 different countries.

The proceedings from the 6th International Temperature Symposium followed the traditional title and volume indexing as in 'Temperature – Its Measurement and Control in Science and Industry' Volume 5. [16] Starting with Volume 5, the publisher would now become the AIP, renewing a vital relationship that went back to the 2nd Symposium in New York where the AIP served as the main sponsor and organizer. The volume was now printed in a full size 'Letter' format and split into just two parts. Schooley served as the Editor in Chief for the Proceedings and was committed to producing a volume of the highest possible quality. A total of 182 papers published in the Volume 5 and it's fair to say that Schooley had edited each of these manuscripts in one way or another. The emphasis was now more on reporting new research and in reviewing the scientific and technological progress over the last decade. The NBS staff contributed 21 of those papers and 100 papers were from authors from outside of the US.

The 'Keynote Address' for the ITS6 was given by Ralph P Hudson, and titled 'Temperature Scales, the IPTS, and its future development'. At the time of the Symposium, Hudson had recently retired from his position at NBS (Deputy Director, Center for Absolute Physical Quantities) and was in his new position of Editor of the journal *Metrologia*, at the BIPM in Sèvres, France. Hudson reviewed all of the progress in temperature scale research that had taken place since the inception of the IPST-68 , discussing the deviations from the kelvin thermodynamic scale and other deficiencies. There was discussion in the CCT at that time concerning what changes might be needed to the IPTS-68 and how a new International Scale might improve thermometry. Hudson addressed all of these questions and discussed both the needs for and impact of a possible new scale.

The IPTS-68 had undergone a minor amendment in 1975 which added the argon triple point (TP) as an optional fixed point for SPRT calibrations, substituting for the O_2 normal boiling point. A senior NBS scientist at the time, George T Furukawa, had been instrumental in developing the metrology necessary to elevate the argon TP to the status of a defined international fixed point suitable for long-stem SPRTs. His paper on that subject was a notable contribution to the proceedings of ITS6.

The 1970s had been a period of rapid innovation in electronics as more functionality was incorporated into integrated circuits, both digital and analog. The advent of commercial 8-bit microprocessors also had an immediate impact on both computing and instrumentation. All of this was evident in the many different innovative instrumentation designs presented at the ITS6. In particular, four separate groups presented new designs for automatically balancing resistance thermometry bridges. One such design paper was written by Robert D Cutkosky, of NBS/NIST, who was a well-known pioneer in electronic instrumentation design. These advances in instrumentation automation had a profound impact on temperature metrology as these new bridge instruments could now collect more data in an automated manner and free up the time of metrologists to perform longer and more complex measurements. This in turn led to greater understanding of the factors limiting the reproducibility of fixed points and SPRTs.

Advances in electronics were also leading to new designs and instruments based on noise thermometry. New techniques for performing noise thermometry had emerged using innovative circuit designs based on a wide variety of both analog and digital methods: from those employing Josephson junction-based superconducting quantum interference devices (SQUIDS);

to one employing a shot-noise diode reference; to a design that employed a digital cross-correlation method. The remarkable feature of noise thermometry was that it could be implemented in different ways to enable the measurement of thermodynamic temperatures from millikelvins to thousands of kelvins. In all, 10 different papers were presented on noise thermometry at the ITS6 with application temperatures ranging from 0.01 K to 1800 K.

Thermocouples and industrial PRTs were finding wider applications in industry and those technologies were being perfected at a new scale of deployment and at higher levels of precision. Some of those advances came from improvements in metallurgy, but the advent of digital electronics had also played an important role. Better amplifiers and digitizers were now available that would greatly improve the measurements, taking signals at the level of tens of millivolts and producing fractional resolution at the level of ten parts per million. Digital instrumentation brought higher throughput and efficiency in general, to both the laboratory and the point-of-use on the factory floor. This in turn led to adoption of national consensus standards for various industrial thermometers. The American Society for Testing and Materials (ASTM) began adopting the now familiar letter-type performance specifications for both base metal and noble metal thermocouples starting in the 1970s. Similar performance specifications were also being developed for industrial PRTs by the ASTM, the British Standards Institution (BSI) and the Deutsches Institut für Normung (DIN). There were 22 separate papers published on all aspects of thermocouples and another 6 papers on industrial PRTs from the ITS6.

Numerous advances in radiation thermometry were reported at the ITS6. New work was ongoing in detectors, including the use of integrated arrays in silicon that could measure temperature distributions across a target area, forming the basis for thermal imaging systems. The ‘narrow-band’ methods and other filter radiometry were being perfected at this time to achieve improved reproducibility and accuracy. These instruments were amenable to calibration using just a few known blackbody radiance temperature standards. The use of computers and fast digitizers was enabling the development of new fast response pyrometers for the study of transient temperature phenomena. Among the pioneers of those methods was Ared Cezairliyan of the NBS Center for Radiation Research. Cezairlian’s group contributed 2 of the approximately 26 papers on radiation thermometry at the ITS6

Advances in laser spectroscopy were taking place in this time period that led to a host of new spectroscopic and laser-based diagnostic methods for temperature measurement in reacting gas flows, flames, and discharges. Methods were being developed based on Raman scattering, correlated anti-Stokes Raman Scattering (CARS), laser-induced fluorescence, Rayleigh scattering, and various laser absorption profiling. These methods allowed probing the real-time temperatures in complex and reacting gas environments in a non-invasive manner. The ITS6 had nine papers on CARS alone, plus another 7 or so papers on absorption and emission spectroscopy.

7th International Temperature Symposium, Toronto, Canada, 1992

The 7th International Temperature Symposium was held from April 28 to May 1 of 1992 in Toronto, Canada. This first-time international venue was accompanied by the sponsorship and close cooperation of the NRC Canada for the organization for the event. Larry Rubin of MIT had returned as chair of the general committee and was assisted by Ronald E Bedford of the NRC Canada. Returning as the program chair, James F Schooley, now of NIST, would once again assemble an excellent technical program. The NBS or the 'Bureau' as it had been known for some 70 years, had become NIST in 1989. The new name was part of legislation that brought a greater emphasis on technology development to its mission. Schooley was able to navigate all of these changes and keep the IT7 program balanced between pure metrology and technology development.

A similar arrangement for the organization of ITS7 was in place to that of the ITS6. The primary sponsors of the ITS7, the ISA, NIST, and the NRC Canada worked to coordinate all the different requirements for holding the Symposium. ITS7 was essentially a sub-conference to the larger ISA Expo event taking place that year at the Toronto Convention Center, and a large technology exhibition was again collocated there.

A new International Temperature Scale had just been adopted prior to the ITS7. The International Temperature Scale of 1990 (ITS-90)[17] had replaced the IPTS-68 and incorporated several important changes to the definitions as well as an extension to the lower temperature range down to a limit of 0.65 K. The new scale and its various new features had generated a great deal of new technical activity and research in both metrology and industrial communities. In particular, a critical change had been incorporated into the ITS-90 where a high-temperature SPRT definition had replaced the previous platinum thermocouple definition in the interval 630 °C to 1064 °C. This change would prove to be problematic and require considerable effort to correct some errors in certain scale conversion tables published in 1990. NIST led an international collaboration of eight National Metrology Institutes that generated new platinum thermocouple reference data forming the basis of those corrections. The results of those investigations were presented at the IT7 and appeared in two papers published in the proceedings, with other related publications to follow in the next two years. The importance of that work was recognized by the NIST management and resulted in the NIST Allen V. Astin Measurement Science Award to the NIST scientific staff, George W Burns, Gregory F Strouse, M Carroll Croarkin, William F Guthrie, and Margaret Kaeser in 1994.

The Keynote Address for the ITS7 was given by Clayton A Swenson of Iowa State University. Swenson's lecture, 'From the IPTS-68 to the ITS-90', reviewed the motivations behind the scale change starting with the deficiencies of the IPTS-68. Those deficiencies were primarily those that were known at the inception of the IPTS-68 and were related to the relative paucity of thermodynamic data over most of the scale's ranges. Furthermore, for those ranges where data did exist, but originating from multiple sources, inconsistencies were found. This was particularly the case for the range between the boiling point of liquid oxygen (O_2 NBP, 90.18 K) and the triple point of equilibrium hydrogen (e-H_2 TP, 13.803 K) where four different gas thermometer scales had been widely discrepant. The ITS-90 had largely resolved many of the

previous deficiencies with the IPTS-68, but one glaring problem remained in particular in the new scale. Two primary gas thermometer realizations, both of which came from NBS, were themselves discrepant by about 30 mK over the range from 500 K to 800 K. The ITS-90 definitions over that range were chosen so that the new scale split the difference between those two data sets. Despite this quandary with the ITS-90, Swenson noted that the uncertainty associated with the new scale was still estimated at a factor of 10 to 100 lower than that of the IPTS-68 at its inception.

The papers presented at ITS7 represented a wide range of topics and technique in temperature measurement. The metrology focus was primarily on various aspects of realizations for the new scale over different ranges and at different laboratories from more than a dozen countries. The technology-focused papers were demonstrating many new capabilities and new instruments, with innovations brought about through advances in digital electronics, detectors, optics and computing. The progress being made in all regions of the world was evident, especially in China, given the more than 30 papers presented from Chinese authors. A few highlights from the proceedings are noted here:

- Thermodynamic methods were being refined and extended in temperature range, including gas-based methods, spectral and total radiation methods, and noise thermometry
- Temperature metrology below 1 K was advancing due the advent of the ^{3}He melting curve thermometer and SQUID-based noise thermometry
- New facilities for the realization of the ITS-90 were being designed and constructed and some new data had already been generated in several NMIs (see the discussion above concerning the interval 630 °C to 1064 °C)
- Sealed-cell methods for the cryogenic non-metal triple points were demonstrating highly reproducible melt plateaus using methods adapted from calorimetry
- New metal fixed point cells were being constructed, tested, and intercompared at several NMIs
- Calibration of high-temperature SPRTs to 1234 K was being implemented and studied extensively
- The rhodium-iron resistance thermometer was finding wider application and development in other countries
- Advances in metal-oxide spinel thermistors were achieving new levels of stability
- High temperature W-Re-based thermocouples were being studied to extend their stability and application base including deep space missions
- Spectroscopic scattering and absorption methods in hot and reacting gas flows continued its growth and refinement including CARS and fluorescence techniques
- Optical fibers were finding new applications as both optical transmission elements in pyrometers and temperature sensors
- New methods were being developed in radiation thermometry to accurately correct or otherwise account for the most common errors from emissivity and reflections
- The temperature measurements required for the processing of silicon wafers in the semiconductor industry was highlighted in several papers

‘Temperature, Its Measurement and Control in Science and Industry’ Volume 6 was published by the AIP in 1992. [18] This volume contained 237 papers, well over half of those were from

international authors and 28 were contributed by NIST authors. This would have been the first ITS proceedings in which the manuscripts' 'galley proofs' were prepared exclusively using word processor computer programs, replacing those previously prepared on typewriters. This technology made the tedious job of editing the proceedings much more manageable. Schooley had adapted to the technology changes and took full advantage of the new capabilities to edit the manuscripts to his rigorous standards for scientific writing. Schooley would retire from NIST shortly after having guided the Proceedings to publication. He went on to author a 1,006-page volume documenting a period of history of the NBS and NIST, "Responding to National Needs, the National Bureau of Standards Becomes the National Institute of Standards and Technology, 1969-1993" which was published in 2000.[19]

8th International Temperature Symposium, Chicago, IL, 2002

Lawrence Rubin, MIT.
Credit: NIST

The 8th International Temperature Symposium (ITS8) was held at the McCormick Convention Center in Chicago IL on October 21 to 24 of 2002. MIT's Lawrence Rubin would again serve as the General Chair, his third and final reprise in that role. The ITS8 was once again hosted and sponsored by the ISA, in cooperation with NIST. The arrangements with the ISA were similar to those of recent symposia, with NIST as a co-sponsor, responsible for the technical program, and the ISA managing the arrangements and financial matters.

The International Program Committee for ITS8 was led by NIST's Dean C Ripple, then Group Leader for Thermometry in the Process Measurements Division. Ripple assembled a team of NIST staff to coordinate all the preparations and worked closely with the Rubin, the ISA, and the rest of the General Committee to make the ITS8 successful. Ripple also served as editor in chief for the proceedings, which were again published by the AIP. Continuing the tradition begun by Schooley two decades prior, Ripple and his teams of assistant editors worked to produce a volume with a quality comparable to that of an archival scientific journal. 'Temperature, Its Measurement and Control in Science and Industry' Volume 7 [20] would be the first in the series to become digitally archived, and is available from the AIP by subscription to its Conference Proceedings Series. The volume 7 contained 200 papers, 20 of which were contributions by NIST authors and 130 by international authors. The disappointment came, however, when visa delays prevented any Chinese scientists from attending the ITS8. Nonetheless, a number of papers from colleagues at NIM Beijing were accommodated and published in the proceedings.

The keynote Speaker for the ITS8 was Hratch G. Semerjian, then Director of the NIST's Chemical Science and Technology Laboratory, who presented a lecture on 'Temperature Metrology and Its Impact on Industry'.[21] Semerjian was himself an expert in spectroscopic temperature measurement methods, having done some of the earlier work on laser tomography that was presented at the ITS6. He would go on to become the NIST deputy director and served as acting director following Arden Bement's departure in 2004. Semerjian spoke about the specific needs for traceable temperature measurements across all industrial sectors, from manufacturing, transportation , medicine, to oil and gas, and more. He discussed the roles of traceability, standardization, instrumentation development and international temperature scales supporting trade and commerce.

Hratch G Semerjian, NIST. Credit: NIST

The papers presented at ITS8 documented the progress in temperature measurement science and technology in a wide range of temperatures and applications. The ITS-90 had been in place for 12 years at that point and the period time going back to the last Symposium in 1992 was marked by a number of refinements in scale realizations and temperature metrology. In addition, a wide range of new methods, technologies, and applications were reported. A few of these developments are highlighted here:

- A new ultra-low temperature scale, the provisional low temperature scale of 2000, was established extending two decades lower in temperature than the ITS-90
- International teams of researchers had begun to precisely determine isotopic corrections for the fixed-point definitions for water and equilibrium-hydrogen.
- New designs were under development for both non-metal and metal-type fixed point cells.
- New thermodynamic temperature realizations were being conducted based on high-temperature acoustic resonators, new quantum-based noise thermometers and infrared filter radiometers.
- Platinum resistance thermometers were being extended for use upward in temperature
- New methods for testing and calibration of thermocouples were under development
- New quantum detectors made from InGaAs were being utilized for infrared radiation thermometry extending the spectral range out to 1.5 μm, allowing temperature measurements closer to 400 K
- New methods were being developed utilizing optical fibers for temperature sensing
- New applications were being developed utilizing various phosphor coatings and solutions to remotely sense surface temperatures as well as in microfluidic systems.
- New methods were reported for high temperature transient thermometry as applied to semiconductor processing and electrochemical discharge machining
- Several international comparisons were either underway or completed, establishing the degree of equivalence between the realizations of the ITS-90 across various NMIs.

There were many interesting and groundbreaking papers presented at ITS8. But we'd like to mention one NIST contribution in particular. The paper 'Fluorescence Thermometry in Microfluidics' described the techniques developed at NIST for the use of fluorescent molecules in solution to measure fluid temperatures within the boundaries of microchannels. Systems of microfluidic channels and volumes have been fabricated for the precise control of solutions and reactants as used in analytic chemistry and biochemistry. The authors were David Ross, of the NIST Cellular Engineering Group and Laurie E. Locascio, our current NIST Director.

Laurie E Locascio, director NIST, 2022
Credit: NIST

The ITS8 had several commercial exhibitors with temperature-specific products, but these were only a small fraction of the exhibits within the ISA's much larger technology exhibition. Moreover, the ISA's focus was gradually shifting away from its historical mission of instrumentation and towards automation, a fact that was clearly evident in the overwhelming presence of automation equipment in the exhibits. In fact, the original name for the ISA had even been changed to the "Instrumentation, systems, and automation" society. That diverging trend between the ISA and NIST's metrology focus would continue over time and this would be the last partnering of NIST with the ISA for the Temperature Symposia.

The former director of the BIPM, Terry Quinn, delivered the closing session lecture at ITS8. His lecture, "Life Before, During and After Key Comparisons", described all of the preparations , difficulties, and impacts of the International 'Key' Comparisons that had taken place around the world, both before and since the advent of the 'Mutual Recognition Arrangement (MRA)' in 1999. The MRA was of course the cornerstone of the multilateral reciprocity set up by the CIPM for the certificates of calibration and testing as issued by accredited laboratories throughout the world. This arrangement was critical to ensure that the international free trade of goods and services could remain unimpeded by any technical barriers tied to measurement issues. Today there are 251 institutes participating in the MRA with signatories representing 97 NMIs.

9th International Temperature Symposium, Anaheim, CA, 2012

The 9th International Temperature Symposium (ITS8) was held at the Disneyland Hotel in Anaheim CA in March of 2012. A new general committee chair, Greg Strouse of NIST, had stepped into the leadership position and developed a new partnership with the Measurement Science Conference (MSC) to host the ITS9. The MSC itself had a long history of holding training workshops and metrology symposia in the southern California region and had been a NIST partner for those purposes for more than 15 years prior. The MSC would hold their annual training symposium in parallel with the ITS9, together with a technology exhibition. This partnership proved successful due to the excellent working relationship between the NIST and MSC staff members. Strouse went on to

become a Senior Advisor to the Associate Director for Laboratory Programs at NIST (his present position).

Strouse assembled a team of people from his group in the NIST Sensor Science Division to recruit the International Program Committee, develop the technical program, and make the arrangements for publishing the proceedings with the AIP. The program committee duties were split between Weston Tew and Howard Yoon, and Christopher Meyer was chosen as the Editor of the Proceedings. The program for the ITS9 was significantly changed from past Symposia due to the incorporation of poster sessions for the first time in the history of the series. The poster sessions were held in the exhibit hall and this was a successful arrangement to keep all the participants together and fully engaged.

The keynote speaker for the ITS9 was Michael Kühne, then Director of the BIPM. Kühne's lecture was titled "Redefinition of the SI" and was held as a joint session between the ITS9 and the MSC. Kühne spoke about the pending changes to the International System of Units (SI) that were scheduled to go into effect in 2019. Among those changes would be the change in the definition of the unit kelvin for thermodynamic temperature. In that case the Boltzmann constant, k_B, would be fixed in its value, rather than being subject to experimental determinations, and the triple point of water would lose its special status as an SI unit definition.

The plans for the new SI would in fact generate a great deal of activity in the realization of thermodynamic temperature as many experiments were either planned or already had begun to redetermine the Boltzmann constant. Seven papers were presented at the ITS9 describing such efforts across as many groups and NMIs over the world. Many of those efforts were described in the opening Plenary talk by Joachim Fischer of the PTB, "The IMERAPlus Joint Research Project for Determinations of the Boltzmann Constant". This project was a large European effort by 10 separate NMIs to support work on the Boltzmann constant in preparation for the new definition. The project concerned three methods for performing the required primary metrology: Dielectric Constant Gas Thermometry; Acoustic Gas Thermometry; and Doppler Broadening techniques.

Michael Moldover, NIST. Credit:

The second presentation of the ITS9 Opening Plenary Session was given by NIST Fellow Michael ('Mike') Moldover, "Primary Acoustic Thermometry: Lessons Learned from 7 K to 600 K". Moldover had pioneered and perfected the methods of Acoustic Gas Thermometry over a 33 year time span (since 1979) as applied to spherical and spheroidal acoustic gas resonators. The resonator method was a powerful technique to determine the thermodynamic temperature via the fundamental relationship between temperature and the speed of sound. When the temperature was held constant near the triple point of water temperature (273.16 K), the method produced a highly accurate value for the Boltzmann constant. Moldover, *et al* [22] first used this method and published a value for the gas constant ($R=N_A k_B$) in 1988. Later, methods were refined which allowed the resonator volume to be determined using microwaves and other laboratories began making their own acoustic gas resonators and publishing results on both thermodynamic temperature and on k_B. These efforts

eventually led to the value for the Boltzmann constant that is now used (since the 2019 redefinition) for the definition of the unit kelvin in the new SI.

For the ITS9, a new editor stepped forward from the NIST staff to follow in Schooley's footprints. Christopher Meyer had to manage a wide range of editing and publishing challenges and working tirelessly with the AIP to produce the print and digital editions of the proceedings. 'Temperature, Its Measurement and Control in Science and Industry' Volume 8 was published by the AIP in 2013.[23] The volume 8 contained 180 papers, the majority of which were contributed by international authors and 14 written by NIST authors.

Looking Forward: the 10th International Temperature Symposium, Anaheim, CA, 2023

The 100th anniversary of the Temperature Symposia came (and went) in 2019. While planning for the next event in the series, the 10th International Temperature Symposium, was already underway, it was clear that celebration of this anniversary would be delayed by another 2 years at least. The initial plan was to hold the event in 2021, but by mid-2020, it was clear that the global pandemic would make that impossible. The same NIST-MSC partnership that organized the previous Symposium in 2012 was in place and working to find a viable path forward. It was decided that the ITS10 would need to be further delayed until 2023.

The rescheduled ITS10 will take place in April 3rd to 7th 2023 and preparations are in the final stages. Experience with other live 'face-to-face' conferences held during 2022 has shown that these events are once again viable, but that the attendance is typically 60 % to 70 % of prepandemic levels. Global health concerns, economic uncertainty and regional conflicts continue to make international gatherings like the Symposia more difficult. Nonetheless, our venue remains open for business and is welcoming visitors from throughout the world once again. While we are planning for a smaller symposium for ITS10 compared to ITS9, the program will be just as timely and relevant to the ongoing progress in temperature measurement research and development. We anticipate that this Symposium will carry on the tradition of excellence in the scientific and technical presentations and in the archival quality of its proceedings.

The ITS10 will mark the centenary of the Temperature Symposia through special recognition of its past organizers and the many scientific and technical contributions made in those previous nine Symposia. We will carry over some traditional aspects of the Symposia past, but also introduce new components in the ITS10 which will augment its relevance and impact to the scientific and industrial communities. The technical program will be incorporating humidity and trace moisture measurement for the first time. This is a practical recognition that humidity and trace moisture standards are in fact temperature standards, as in the well-defined dew-point and frost-point temperatures. Another significant change will take place in the ITS10 program as we will be incorporating training workshops for the first time. These workshops are planned as a series of introductory lectures on temperature and humidity measurement practice, provided by the NIST scientific staff, and open to any and all attendees of both the ITS10 and the MSC 2023 events. The program and abstracts will be available for the first time in two new all-digital

formats. First, the conference digest will be made available in electronic form as a pdf file for download and published by NIST as a Special Publication Series 2100 document. Second, a mobile App will be available that contains information on the Symposium program, schedule, venue, sponsors, and news.

We will be replacing the traditional keynote address with a special honorary lecture in memory of Jim Schooley, who passed in 2020 at the age of 88. Graham Machin of the NPL will be presenting the Schooley Plenary Lecture at ITS10. Machin's lecture will focus on the new temperature measurement research being performed in response to the change in the definition of the kelvin that occurred in 2019.

Other Plenary sessions are being planned that will bring several interesting topics into focus for the ITS10. "Frontiers in Temperature Measurement" will feature two speakers currently working on research that could revolutionize how we measure spatially-resolved temperatures in three dimensions using non-invasive methods. XiaoJuan Feng of the National Institute of Metrology in Bejing, China will speak on new applications of nitrogen-vacancy nanodiamonds for probing temperatures at sub-micrometer size scales. Thinh Bui of NIST will be speaking on the use of magnetic nanoparticles for spatially-resolved temperature measurement in 3-dimensional and optically-opaque applications.

Another planned plenary session is "Trends in Industrial Temperature Measurement". This session will feature presentations by Steffen Rudtsch of the PTB and Louise Wright of the NPL. Rudtsch will speak on temperature metrology needs for high-tech industries and critical infrastructure. Wright will present on the subject of digital metrology and its potential benefits and caveats for industrial temperature measurement. Both subjects are forward looking, using our experience and understanding gained in the science and technology of temperature measurement to predict how innovations will continue to present both new opportunities and significant challenges in metrology and engineering.

A special climate-focused session is planned for Thursday morning, "Temperature, climate and human health". Our first speaker will be David Romps, professor of Climate Physics in the Department of Earth and Planetary Science at UC Berkeley. Romps will present his recent research on the heat index, its importance in a warming climate and new efforts to improve its utility under higher temperature and humidity conditions. Our second speaker will be Sarah Purkey of the Scripps Institution of Oceanography, University of California, San Diego. Purkey will speak on ocean temperature observations and the oceans' role in earth's climate.

Finally, our closing session for the ITS10 will feature Patrick Rourke of the NRC Canada who will speak on the Future of the International Temperature Scale. A panel discussion will follow Rourke's presentation as we conclude the 10th Symposium with a look forward to the future and the next chapter in the history of the Temperature Symposia.

Conclusions

The Temperature Symposia have both endured and evolved during the now more than one century since their inception. The progress in the science and technology of temperature metrology is evident as we reflect back on this past as recorded in their proceedings. These are probably among the longest continuous series of such symposia in the western hemisphere. What started out as a purely American gathering of scientists, has evolved into a truly international

event with global participation. With such long intervals of a decade or more between events, the continuity provided by NBS and now NIST has been critically important. While the individual staff leading the organization of the Symposia have turned over multiple times over these generations, their dedication to the mission of advancing the field has been steadfast.

The 2023 Symposium, like that of the 1919 meeting, comes at the conclusion of a global pandemic. The complete impact of the current crisis has yet to be fully tallied, but we continue to see a cascade of global economic disruptions with far reaching consequences. The ITS10 has had to adapt to these disruptions and the accompanying economic uncertainties. This makes the planning of this or any other live event very difficult and elevates the financial risks for the sponsors. We should all recognize this reality and acknowledge the difficult choices it forces in making the arrangements for the event. Please take a minute to thank the members of the Measurement Science Conference Board of Directors for their dedication and courage in the face of these risks and the service they provide to our scientific and engineering communities.

As both society and technology continue to change with time, so do our modes of communication and professional collaborations. As expected, the role of scientific and technical conferences such as the ITS will need to continue to adapt and change to accommodate these new modes. The gradual changes that had been already occurring were then made abrupt by the pandemic, and we have struggled to find our way back to a new normal. The live face-to-face conference is still an important way to interact with colleagues from different countries and different communities, and the NIST staff are trying to keep that tradition alive and available by holding the ITS10 as such an event. We look forward to connecting with all of our international and domestic colleagues and stakeholders in Anaheim this April.

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Opening Session A: James F Schooley Plenary Lecture

For the ITS10, we instituted a first memorial lecture in honor of James Frederick Schooley (August 24, 1931 – April 18, 2020), a distinguished chemist who spent his career at the National Institute of Standards and Technology (NIST). Schooley was an accomplished and prolific writer, researcher, leader, and editor. More information about Schooley and others who were vital to the continued operation of ITS can be found in the Introduction.

Progress with realizing the redefined kelvin
Graham Machin (National Physical Laboratory, United Kingdom (Great Britain)); Mohamed Sadli (LNE-Cnam, France); Jonathan Pearce (NPL, United Kingdom (Great Britain)); Alexander Kirste (PTB, Germany); Jost Engert (Physikalisch-Technische Bundesanstalt, Germany); Roberto Gavioso (INRiM, Italy)
Invited

Invited

Progress with realizing the redefined kelvin

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In May 2019 four of the base units of the international system of units (the SI) were redefined in terms of fundamental constants [1]. From that point on the SI was based on atomic properties (the second), fundamental constants (the metre, the kilogram, the ampere, the kelvin, the mole) or a conventional constant (the candela). The kelvin was redefined in terms of the Boltzmann constant *k* [2, 3] concluding over a decade of effort by the international thermometry community to redetermine *k* with low uncertainty [4].

Accompanying the redefinition were practical guides whose purpose was to guide the user from the definition of the unit to a practical realization. For the kelvin this document was known as the *mise en pratique* for the definition of the kelvin [5] and was designated *MeP*-K-19 to identify that the 2019 version of the *MeP*-K was in force from the time of the redefinition.

The kelvin redefinition, and the associated *MeP*-K, stimulated new opportunities for realization and dissemination of the temperature unit. Presently most of temperature traceability is provided through the defined scales; either the International Temperature Scale of 1990 [6] or the Provisional Low Temperature Scale of 2000 [7], but in the future temperature traceability, directly to the kelvin definition, is likely to become more widespread [3, 8].

Here we describe the progress made in realizing some of the primary thermometry approaches promoted in the *MeP*-K-19 that could be used for providing direct traceability to the kelvin. This will be done in the context of the European Metrology Programme for Innovation and Research (EMPIR) research project "Realizing the Redefined Kelvin" (Real-K) [1] though other work in the field, where relevant, will also be introduced. The impact of these developments on traceability to the kelvin will be discussed, as will the emergence of *in-situ* traceability through practical primary thermometry and self-calibrating thermometers [8].

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Parallel Session B1: Thermodynamic Temperature I

Updated Differences Between Thermodynamic- and ITS 90 Temperature - a pathway to improvements in metrology and beyond
Christof Gaiser (PTB, Germany); Bernd Fellmuth (Physikalisch-Technische Bundesanstalt (PTB), Germany)
Invited

1500 s settling-time optical RIGT, and relative determination of T - T_90 across (293 < T < 433) K
Patrick Egan (NIST, USA)

New NRC Acoustic and Refractive-Index Gas Thermometer
Patrick M.C. Rourke (National Research Council Canada, Canada); Donald J. Woods (National Research Council of Canada, Canada); Michel B. Levesque and Andrew Todd (National Research Council Canada, Canada)

Invited

Updated Differences Between Thermodynamic- and ITS 90 Temperature - a pathway to improvements in metrology and beyond

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In 2011, a working group of the Consultative Committee for Thermometry published their best estimates of the differences between the thermodynamic temperature T and its approximation (T_{90}), the temperature according to the International Temperature Scale of 1990, ITS 90. Since 2011, there has been a change in the definition of the kelvin and significant improvements in primary thermometry. A recent paper [1] updates the (T - T_{90}) estimates by combining and analyzing the data used for the 2011 estimates and data from more recent primary thermometry. The new data has been obtained by four types of gas thermometry: acoustic, dielectric constant, refractive index, and constant volume. Their uncertainty estimates are now comparable with the uncertainties in the best measurements of thermodynamic temperature values and the uncertainties in ITS-90 realizations. The results presented in [1] are the basis for the planned updating of the annex *Estimates of the differences $T - T_{90}$* of the *Mise en pratique for the definition of the kelvin in the SI* [2]. For users without primary thermometry capability, it is now possible to access thermodynamic temperature values T below 335 K with comparably small uncertainties via an ITS-90 calibration and the transfer applying (T - T_{90}). This is a way to bridge the existing gap between enormous effort for T measurements and comparably good access to T_{90}.

The applications in this field are divers and increase with demands for decreasing uncertainties. An example in metrology is the prospering field of alternative pressure standards with T as one of the key parameters. The idea, first expressed in [3], is now tested on a level of 2 ppm [4] at the triple-point-of-water temperature T_{TPW}. This is only possible if T is known on the 1 ppm level which is comparably easy to achieve at T_{TPW}. However, pressure standards are usually operated at room temperature. For such applications, the existing difference (T - T_{90}) of order 3 mK must be known with very small uncertainties. Another example is the field of thermophysical properties where ab initio calculations of gas properties have made enormous progress. To check the theory by experiment, highly accurate measurements are needed. But theory evidently is based on T, whereas the experiments are made with thermometers carrying T_{90}. In the case of the second density virial coefficient of helium, both, theory [5] and experiment [6] have now reached relative uncertainties on the 0.01% level or better. For specific features and temperature ranges, (T - T_{90}) must be considered. In the future, it is very likely that the group of users will increase, and with new measurements in the temperature range above 335 K, the range of low uncertainty (T - T_{90}) estimates will be extended.

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1500 s settling-time optical RIGT, and relative determination of $T - T_{90}$ across $(293 < T < 433)$ K

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An optical refractive-index gas thermometer [1] determined $T - T_{90}$ in the temperature range $(293 < T < 433)$ K within about 3 µK/K relative standard uncertainty. The thermometer is based on an optical resonator operating at 633 nm wavelength. The working principle first measured helium refractivity at known pressure and temperature to determine the temperature-dependent compressibility of the resonator. With accurate knowledge of compressibility, the resonator was then run with argon to determine $T - T_{90}$ via $T \approx \frac{3A_R}{2R}\frac{p}{n-1}$. The molar polarizability A_R of argon was dependent on best-knowledge of thermodynamic temperature at the gallium melting-point; consequently, the implementation is relative primary thermometry [2], with one key-parameter value tied to $T - T_{90}$ near 303 K.

This gas thermometer effort included the establishment of a state-of-the-art piston-gage pressure scale; uncertainty in gas pressure (1.9 µPa/Pa) is the dominant contributor to measurement uncertainty. However, in any single isotherm regression, the $n(p,\ t_{90})$ triplets exhibit statistical consistency within 0.5 µK/K. A single isotherm took 85 h to acquire, comprising 19 set pressures up to 500 kPa repeated 5 times. Various aspects of the isotherm regression will be discussed; the focus will be on the linear term which contains information on T, but the nonlinear terms are also of interest to ongoing developments in laser barometry [1].

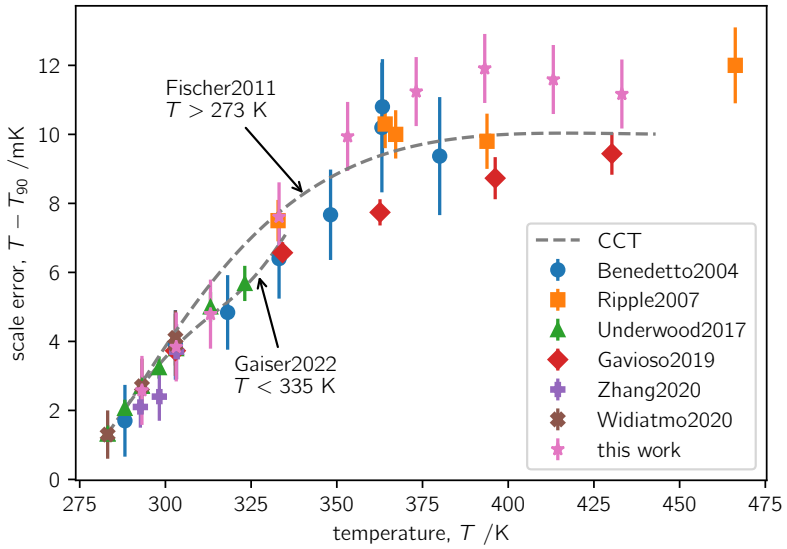

Fig. 1. Measurements of the scale error in ITS-90.

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New NRC Acoustic and Refractive-Index Gas Thermometer

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A new Primary Gas Thermometer facility has now come online at the National Research Council Canada (NRC). This apparatus was created to enable simultaneous acoustic gas thermometry (AGT) and refractive-index gas thermometry (RIGT) in the same gas volume, applying the lessons learned from the previous NRC RIGT system.

In addition to incorporating acoustic measurement infrastructure, the new cryostat is optimized for improved temperature, thermal gradient, gas pressure and gas flow capabilities. The new quasi-spherical resonator (QSR) was purchased from LNE-Cnam in France, built according to their successful BCU3 design.

The planning, construction and testing of the AGT+RIGT cryostat and assembly of the QSR will be described, including tuning of the resonator hemispheres, microwave antennas, acoustic microphones, and associated instrumentation. Temperature-dependent microwave vacuum characterization measurements of the new A1 copper BCU3 resonator will be compared to those of the old OFHC copper racetrack resonator used previously at NRC.

Since NRC is new to the AGT field, our chosen acoustic model and approach to acoustic corrections will be discussed, including resolving inconsistencies found in the existing AGT literature.

Lastly, the results of two proof-of-concept absolute single-state AGT & RIGT measurements will be presented: one using argon gas at room temperature and the other using helium gas at the temperature of the triple point of water. These measurements incorporate all components of the new facility, and serve to highlight the similarities and differences between the acoustic and refractive-index routes to realizing the new kelvin.

Parallel Session B2: Radiation Thermometry I

8 µm to 14 µm Thermal-Infrared Radiation Thermometer Calibrated with ITS-90 Fixed-Point Blackbodies
Howard Yoon and Vladimir Khromchenko (NIST, USA)

Non-contact Temperature Calibration Capabilities of the Physikalisch-Technische Bundesanstalt for Temperatures from -60 °C to 962 °C
Ingmar Mueller (Physikalisch-Technische Bundesanstalt (PTB), Germany); Christoph F. Hemeling (TU Ilmenau, Germany); Julian Gieseler (Laboratory for Atmospheric and Space Physics, Germany); Jörg Hollandt and Christian Monte (Physikalisch-Technische Bundesanstalt, Germany)

The Development of The Vacuum Infrared Radiance Temperature Standard Facility
Jian Song and Xiaopeng Hao (National Institute of Metrology, China)

Long Term Behavior of Radiation Thermometers with Pyroelectric Detectors
Frank Liebmann (Fluke Corporation, USA)

8 µm to 14 µm Thermal-Infrared Radiation Thermometer Calibrated with ITS-90 Fixed-Point Blackbodies

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Due to improvements in the performances of thermal infrared detectors, radiation thermometers (RT) which operate in the 8 µm to 14 µm spectral region are commonly available and used to measure objects that range in temperature from 35 °C to over 500 °C. Often these RTs are calibrated using small, portable flat-plate blackbodies (BB) which, in turn, need to be calibrated by the use of standards-quality transfer RTs. The lowest uncertainties in these BB calibrations can be achieved if ITS-90 fixed-point BBs could be used directly to calibrate these transfer RTs. Currently, commercially available transfer RTs have large size-of-source effects (SSE) or have limited temperature ranges so that the use of a single transfer RT which can cover the entire temperature region has not been possible.

We describe the design, construction and characterization of an 8 µm to 14 µm thermal infrared RT which has sufficiently low SSE and wide temperature range so that a water-bath BB and ITS-90 fixed-point BBs from In- to Al-point with 6 mm diameter cavities can be used for calibrations. The target size of the RT has been designed to be about 4 mm at a distance of 40 cm using a field-stop diameter of 1.38 mm. This design is a modification of a previously published design which uses ZnSe optics and thermo-electric stabilized internal tube [1]. The field stop which is made of mirror-polished stainless steel is tilted by 11 ° from the optical axis. This tilt functions to divert the reflected thermal radiation away from the objective lens in order to reduce the SSE and also to direct the visible radiation to an optical telescope. The optical telescope is used for visual alignment of the small target onto openings of ITS-90 fixed-point BBs. To reduce the SSE, a Lyot stop is also used. Figure 1 shows the SSE measured with this design. Figure 2 shows the measured signals using a variable-temperature BB set at ITS-90 fixed point BB temperatures. The fitted line in Fig. 2 is a modified Sakuma-Planck interpolation with a constant offset term.

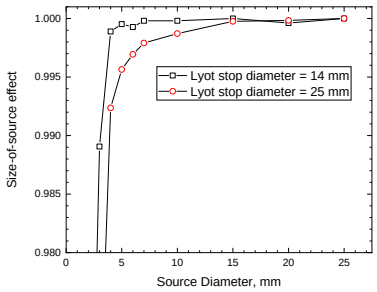

Fig. 1. SSE measured using two different Lyot-stop diameters.

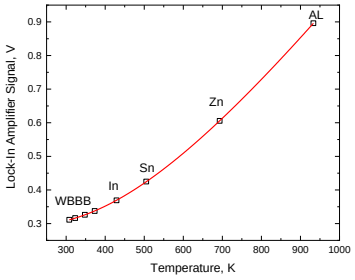

Fig. 2. Measurements performed using a variable-temperature BB to demonstrate the range in operational temperatures. A Sakuma-Planck interpolation function fit is shown.

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Non-contact Temperature Calibration Capabilities of the Physikalisch-Technische Bundesanstalt for Temperatures from -60 °C to 962 °C

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The current low temperature infrared calibration facility of the Physikalisch-Technische Bundesanstalt (PTB) [1], which has been in continuous operation for more than 20 years, will be completely overhauled in the next few years. Thus, a new facility had to be put into operation in order to be able to offer our calibration service seamlessly at the highest metrological level during the thorough maintenance and repair period of the original facility. This new facility marks the state-of-the-art for calibrating infrared radiation thermometers, thermal imagers, and blackbodies from -60 °C to 962 °C at PTB. After the renewal of the original calibration facility both facilities will be continuously operated in parallel for research and customer calibrations.

Four different heat pipe blackbodies provide radiant temperatures with uncertainties that are among the lowest in the world. A high-precision positioning system (travel ranges of (3 x 0.6 x 0.4) m (l x w x h)) enables pixel-wise displacement of thermal imagers, necessary for applying the so-called “Data-Reference-Method” [2]. With this correction method, no additional calibration uncertainty is introduced which usually results from the inherent spatial temperature nonuniformity of the calibration source. In this case the infrared imager is adjusted and positioned in relation to a detector reference pixel, requiring a single-pixel accuracy of the positioning system. In combination with a gimbal, the devices under test, e.g. radiation thermometer, can be aligned automatically in horizontal and vertical direction setting the right rotation and tilt angle. Up to four devices can be calibrated in parallel.

The calibration facility has been characterized thoroughly by combining different radiometric measurements such as emissivity measurements of reference samples that mimic the cavity walls, radiometric measurements of the temperature distributions along the cavity walls, Monte-Carlo raytracing simulations of the temperature profiles and effective emissivities as well as solving the heat flow equations for the heat pipe cavities (**Fig. 1.** and **Fig. 2.**)

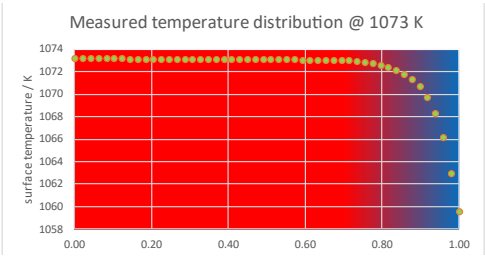

Fig. 1. Temperature distribution along the cavity wall of a sodium heat pipe blackbody at 1073 K obtained from radiometric measurements and iterative Monte-Carlo-Simulations.

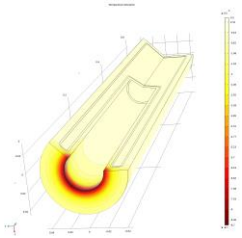

Fig. 2. Temperature distribution of a sodium heatpipe at 1073 K, calculated using an FEM simulation.

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The Development of The Vacuum Infrared Radiance Temperature Standard Facility

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Infrared remote sounders are moving toward having high-spectral resolution and high quantification. In the fields of climate change observation and numerical weather prediction, the timely detection of radiance signals requires measurements with a high level of accuracy. It poses huge challenges to the design of infrared remote sounders and the radiance calibration.

The new generation of Vacuum Infrared Radiance Temperature Standard Facility (VIRTSF) for Infrared radiance temperature calibration and the spectral emissivity measurement is established at NIM China. The blackbodies used as the pre-flight and in-flight radiometric reference of infrared remote sounders can be calibrated in VIRTSF under vacuum and controlled background. The vacuum chamber for blackbody under test was designed to be work at controlled background radiation, which makes the calibration performed under similar conditions of the blackbody as found in final working status to minimize the measurement uncertainty. The values of standard blackbodies in VIRTSF are traceable to the International Temperature Scale (ITS-90). The standard blackbodies, including the variable temperature blackbodies and the fixed-point blackbodies, are designed. The radiance temperature of the customer blackbodies are calibrated by the standard blackbodies through a Fourier transform infrared spectrometer [1].

The temperature range of the new designed standard blackbody is from 125 K to 500 K with a 30 mm in diameter and 0.9997 emissivity of the cavity. The radiance temperature standard uncertainty of the blackbody is 0.026 K@300 K/10μm [2]. The fixed point blackbodies include a mercury blackbody, a gallium blackbody and an Indium blackbody. The cavities diameter are all 25 mm, and the uncertainty of the fixed blackbodies is 0.03 K@300 K. The system could support the requirements of lots of infrared remote sensing payloads.

Fig. 1. The new generation of Vacuum Infrared Radiance Temperature Standard Facility.

Table 1. The Standard Uncertainty of the VIRTSF (K).

Wavelength / *T*	***3μm***	***6μm***	***8μm***	***10μm***	***16μm***
125				***0.69***	***0.22***
150				***0.29***	***0.22***
190			***0.09***	***0.08***	***0.05***
250		***0.07***	***0.06***	***0.05***	***0.05***
300	***0.08***	***0.03***	***0.03***	***0.03***	***0.05***
350	***0.04***	***0.03***	***0.03***	***0.03***	***0.05***
400	***0.04***	***0.03***	***0.03***	***0.03***	***0.06***
450	***0.03***	***0.02***	***0.03***	***0.04***	***0.06***
500	***0.03***	***0.02***	***0.03***	***0.04***	***0.07***

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Long Term Behavior of Radiation Thermometers with Pyroelectric Detectors

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While photon detector-based radiation thermometers form the basis for primary traceable radiation thermometry above the silver-point, their use below the silver point is limited due to lack of thermal radiation at lower temperatures. There is some work being done with these type of detectors down to 0 °C. However, in this region, there are radiation thermometers being used for traceable calibration work which are pyroelectric detector-based instruments. This family of radiation thermometers went under great scrutiny as traceable instruments during the TRIRAT project.

Fluke Calibration's American Fork Laboratory has established traceability using radiation thermometers with pyroelectric detectors. The work on this project began in 2006, with traceable calibrations being done starting in 2007. Since this time, a significant amount of data has been accumulated on four reference standards. The data are applied to these standards for use in calibrating flat plate thermal radiation sources. The data are also used as a quality control on each radiation thermometer's drift.

This paper presents this drift history of over 15 years. It discusses the initial drift observed on the instruments, plus the steady state drift observed in these instruments. It also looks at the repeatability of these calibrations looking at the variance of these readings over time. An examination of any other time related factors with these radiation thermometers is considered.

Parallel Session B3: Luminescence Thermometry I

Traceable surface temperature calibration device based on thermographic phosphors
Aldo Mendieta and Gavin Sutton (National Physical Laboratory, United Kingdom (Great Britain))

Temperature Sensing to above 1500 °C Using Y2SiO5: Er Phosphor Thermometry
Jeffrey Eldridge (NASA Glenn Research Center, USA); John A Setlock (University of Toledo, USA); Kang N Lee (NASA Glenn Research Center, USA)

X-ray Phosphor Thermometry: Energy Dispersive X-ray Diffraction
Caroline Winters, Linda E. Hansen, Daniel R. Lowry, John C. Miers and Eric R. Westphal (Sandia National Laboratories, USA)

Highly Temperature Sensitive Delayed Luminescence from Gd2O2S: Eu
Stephen Allison (Emerging Measurements, USA); Michael R Cates (Emerging Measurements Co., USA); Firouzeh Sabri and Debendra Timsina (University of Memphis, USA)

Traceable surface temperature calibration device based on thermographic phosphors

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Accurate, traceable temperature measurement is important for improving process efficiency in industry. The development of innovative thermometry techniques to address limitations of conventional techniques requires metrological validation to fully establish these as a viable alternative. Here we propose a highly sensitive and traceable calibration prototype for phosphor thermometry as well as in-house developed uncertainty modelling tool to ease the implementation of traceable surface thermometry. Phosphor thermometry has been successfully applied to many fields (nuclear, steal processing, combustion, etc.) where remote acquisition and minimal intrusion are desired. In phosphor thermometry, the temperature induced changes in the luminescent properties, e.g., decay time, of specialist ceramic powders are exploited for temperature sensing. In the case of surface thermometry, these powders are bonded in the form of thin layers to the surface of interest for remote temperature monitoring [1]. In a similar manor to contact-based techniques, the measured temperature is that of the sensor – the phosphor coating, but in this case, it is interrogated remotely (optically). Even though very thin phosphor coatings are usually applied (< 100 µm), the measured temperature T_{meas} can be different to that of the coating's surface temperature T_{surf} due to the luminescence signal emanating from within a coating with potentially large temperature gradients. To quantify such temperature errors, it is important to understand the different uncertainty components inherent with this optical method. In this work, a 1D steady state heat transfer and optical extinction analysis of a thermal validation phosphor target and design for a prototype phosphor-based surface calibrator, operating between 20 °C to 500 °C, are presented. All estimations are using thermophysical and optical properties of tested coatings containing the phosphor Mg_4FGeO_6:Mn and a ceramic-based binder (Aremco Ceramabind 643-2). The uncertainty evaluation procedure, heat transfer and optical extinction models presented can easily be extended to other phosphors, substrates and/or temperature ranges. Fig. 1 Left shows the design of the phosphor calibration system and Fig. 1 Right shows the temperature difference $(T_{surf} - T_{meas})$ for three coating thicknesses (Lphosphor), showing how the phosphor derived temperature is dependent on coating thickness due to the luminescence signal emanating from different depths.

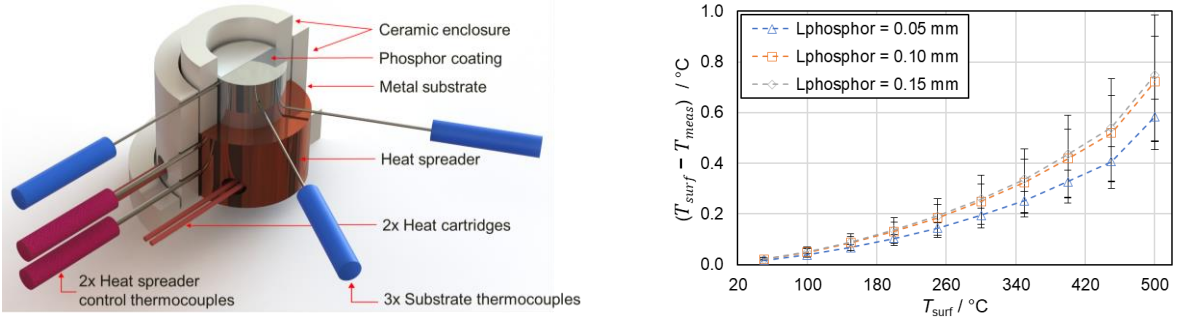

Fig. 1. Left. Design of the phosphor calibration system. Right. Calculated difference $(T_{surf} - T_{meas})$ for three coating thicknesses, for temperatures up to 500 °C. The error bars represent the change in values for a 1 σ change of $\Delta = \pm$ 0.017 mm (coating thickness).

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Temperature Sensing to above 1500 °C Using Y_2SiO_5:Er Phosphor Thermometry

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A transition from metallic to turbine components that can operate at higher turbine engine temperatures will push component surface temperatures from below 1200 °C into a 1300 to 1500 °C temperature range that is much more challenging for phosphor thermometry measurements. To address this challenge, Y_2SiO_5:Er was selected for its high temperature sensing performance by both luminescence lifetime and luminescence intensity ratio (LIR) methods as well as its thermochemical compatibility with the current generation of rare earth silicate environmental barrier coatings (EBCs) that are required to protect SiC/SiC ceramic composite components.

Lifetime measurements that monitor the Er^{3+} $^4S_{3/2}\rightarrow{}^4I_{15/2}$ emission decay at 542 nm exhibited a slow decrease in decay time with temperature up to 1300 °C, above which the decay decreased steeply to provide good temperature sensitivity in the 1300 to 1500 °C range (Fig. 1). LIR images were obtained where each pixel represented the ratio I_{488}/I_{561} (I_{488} and I_{561} are the detected 488 nm $^4F_{7/2}\rightarrow{}^4I_{15/2}$ and the 561 nm $^4S_{3/2}\rightarrow{}^4I_{15/2}$ emission band intensities, respectively). Good temperature sensitivity (Fig. 2) and signal-to-background ratios were observed to above 1500 °C. Contrary to conventional guidance on selecting phosphors for high temperature sensing, the detected emission band intensities and decay times exhibited remarkably slow decreases with temperature up into the 1300 to 1500 °C range despite high phonon energies (>900 cm^{-1}) that allow the energy gap between the $^4S_{3/2}$ emitting reservoir level and the $^4F_{9/2}$ level below it to be bridged by as few as three phonons. The benefit of utilizing a thermographic phosphor at very high temperatures that exhibits strong nonradiative multiphonon relaxation even at room temperature is explained by a competition between spontaneous and stimulated multiphonon emission, and the more temperature-sensitive decay time above 1300 °C is explained by a transition from high to low effective phonon energies.

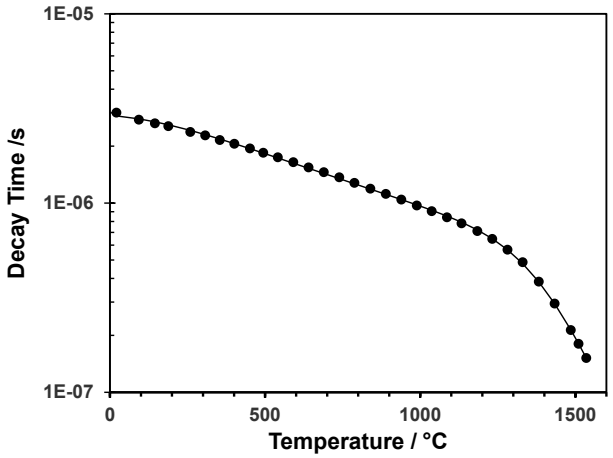

Fig. 1. Temperature dependence of Y_2SiO_5:Er decay time from furnace calibration measurements. Excitation at 522 nm, emission detected at 542 nm.

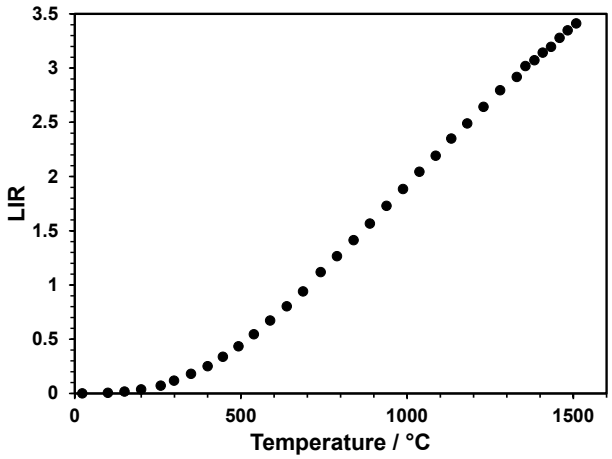

Fig. 2. Temperature dependence of measured Y_2SiO_5:Er area-averaged luminescence intensity ratio (LIR) (I_{488}/I_{561}) obtained from time-gated (1 μs) image.

X-ray Phosphor Thermometry: Energy Dispersive X-ray Diffraction

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When optical luminescence is occluded (e.g. sooty flames), temperature-dependent x-ray signatures may be utilized as a complementary diagnostic to visible phosphor thermometry. Initial temperature sensitivity experiments were performed for terbium doped gadolinium oxysulfide ($Gd_2O_2S:Tb^{3+}$, GOS:Tb) from T = 30 C – 300 C [1] at a synchrotron light source. Energy-dispersive x-ray diffraction (EDXRD) of GOS:Tb,was found to be an excellent candidate due to strong, distinct diffraction peaks which shift linearly with temperature.

In this work, EDXRD experiments were fielded at a laboratory scale with a commercial x-ray tube source (Phillips MCN, Polychromatic 225 keV, 15 mA). This in-house system must be geometrically designed to obtain the necessary 3% energy resolution required. Different detection geometries using 1) pinhole and 2) soller slits are compared at room temperature [2]. This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government. This work was supported by the Laboratory Directed Research and Development program SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525

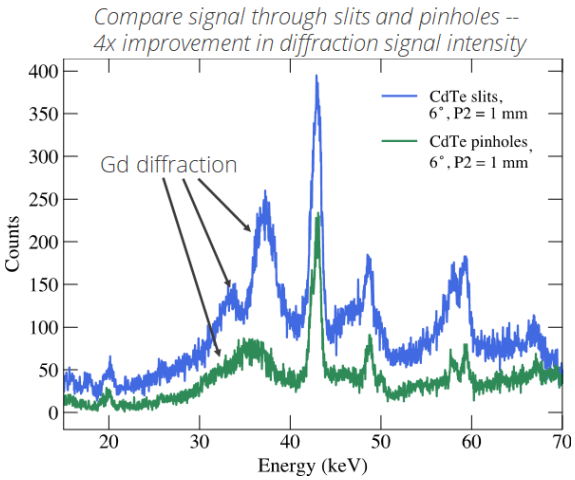

Fig. 1. Energy spectra of GOS:Tb showing both GOS diffraction peaks and x-ray fluorescence from gadolinium and tungsten. Slits (blue) attain better resolution and stronger signal than pinholes (green) as further demonstrated in Fig. 2.

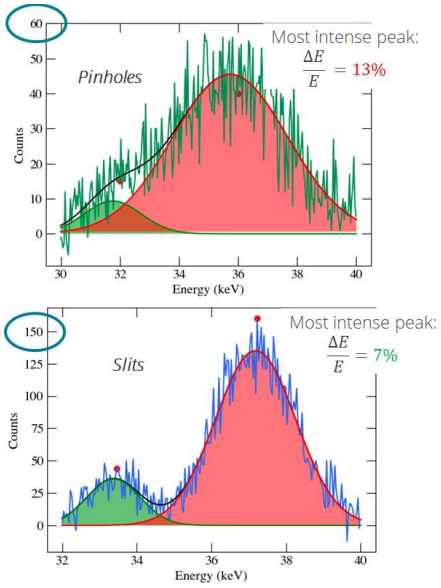

Fig. 2. Energy resolution quantification using Gaussian fitting of two GOS diffraction peaks.

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Highly Temperature Sensitive Delayed Luminescence from Gd_2O_2S:Eu

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The high temperature sensitivity of delayed luminescence from the well-known phosphor Gd_2O_2S:Eu is described. The focus concerns biological temperatures though future research could expand the range. This is a direct follow-up to earlier work [1] that explored the role of excitation pulse duration for eliciting luminescence of emitting states of different extents from a similar material, La_2O_2S:Eu. In significant and instructive work, Katumo et al [2] captured temperature-sensitive delayed fluorescence from Gd_2O_2S:Eu using a smart phone.

Phosphor Technology samples of 1% and 6% Eu were excited by a 365 nm LED of 1 s duration. A thin layer was held in place by quartz window pressing on a copper plate held to a ceramic Peltier heater/cooler ranging from 22 to 56 °C. Both a photomultiplier (PMT) and a pin diode were used as detectors with various bandpass filters and no filter, respectively.

Figure 1 shows three representative decay curves. The decay time, see the inset, clearly decreases with temperature. Looking to early in the decay, the amplitude is increasing with temperature. A value for the amplitude is determined by fitting the decay to a single exponential and extrapolating to time zero. By forming the ratio Q = decay time/amplitude, a very sensitive function of temperature results. Q changes by nearly three orders of magnitude over a range of 40 °C. Figure 2 is a graph of Q. A linear fit indicates a very high relative temperature sensitivity of about 18% per degree.

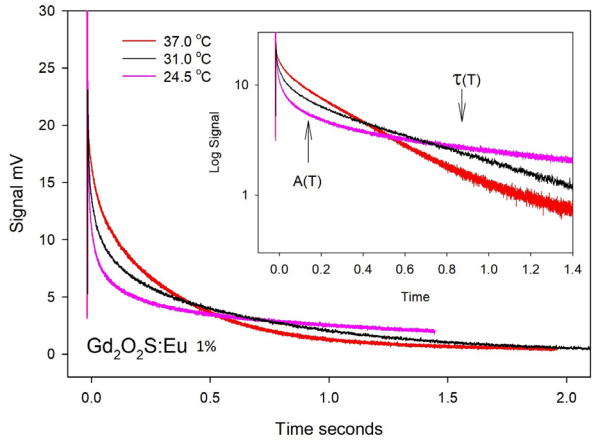

Figure 1. Luminescence signal versus time at 24.5, 31, and 37.0 °C. The inset is a semilog plot of the same. Detector: PMT with 488 nm bandpass filter.

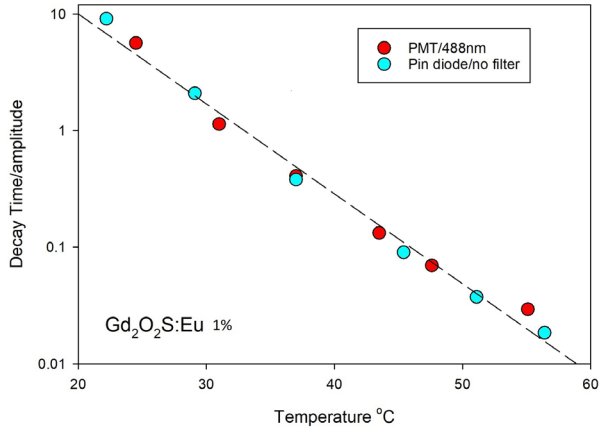

Figure 2. The parameter Q=[decay time/amplitude] versus temperature.

In the presentation and final paper, additional characterizations including scanning electron micrographs will be presented for both dopant concentrations as well as additional data for different excitation, detection and temperature conditions.

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Parallel Session B4: Humidity Standards

Dew Point and Frost Point Metrology

Development of primary measurement standards for trace moisture in multiple gases
Minami Amano and Hisashi Abe (National Metrology Institute of Japan, Japan)

Development of a High-Pressure Dew/Frost-Point Calibration Facility at NIST
Christopher Meyer (National Institute of Standards and Technology, USA)

New BEV / E+E Elektronik High Pressure Dew Point Generator - Design and Proof of Concept
Patrick Raab and Helmut Mitter (BEV EplusE, Austria)

Uncertainty in trace moisture measurements by adsorption/desorption phenomena
Hannu Sairanen (Finland)

Development of primary measurement standards for trace moisture in multiple gases

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In the manufacturing processes of semiconductor devices, many moisture analyzers (MAs) are used to monitor residual trace moisture included in ultra-high purity gases. For calibrating and performance-testing the MAs, we developed a primary measurement standard for trace moisture in N_2 in the range of 10 nmol mol^{-1} to 5 µmol mol^{-1}, and those for trace moisture in Ar, He, and O_2 in the range of 10 nmol mol^{-1} to 1 µmol mol^{-1}. The trace-moisture standards were realized using a generator named "Multi-gas Trace-moisture Generator" which consists of a generation chamber based on the diffusion-tube method and a two-stage dilution system based on critical flow Venturi nozzles [1]. The evaporation rate of water in the chamber was (520.9 ± 1.1) µg h^{-1}. Highly stable flow-rate control of the diluent gas was attained in the two-stage dilution system; the relative stability of the gas flow rate was ≈ 10^{-3} % [2].

The relative expanded uncertainty (k=2) of the trace-moisture standard in N_2 was between 0.41 % and 2.6 %, and the standard was in good agreement with those realized using NMIJ's existing trace-moisture/frost point generators. The relative expanded uncertainty (k=2) of the standards in Ar, He, and O_2 was 0.73 % − 2.6 %, 0.74 % − 5.7 %, and 0.78 % − 8.9 %, respectively. The uncertainty budgets will be reported. A commercial MA based on the cavity ring-down spectroscopy (CRDS) was connected to the Multi-gas Trace-moisture Generator as a device under test (DUT), and the performance in N_2, Ar, He, and O_2 was tested by comparing its readings with the standard values. The accuracy and stability of the CRDS-based MA changed according to the gas. This is because the pressure-broadening coefficient of water is dependent on the gas species. The gas-type dependence of the performance of CRDS-based MAs will be discussed.

This study was supported in part by JST, CREST Grant Number JPMJCR2104, Japan.

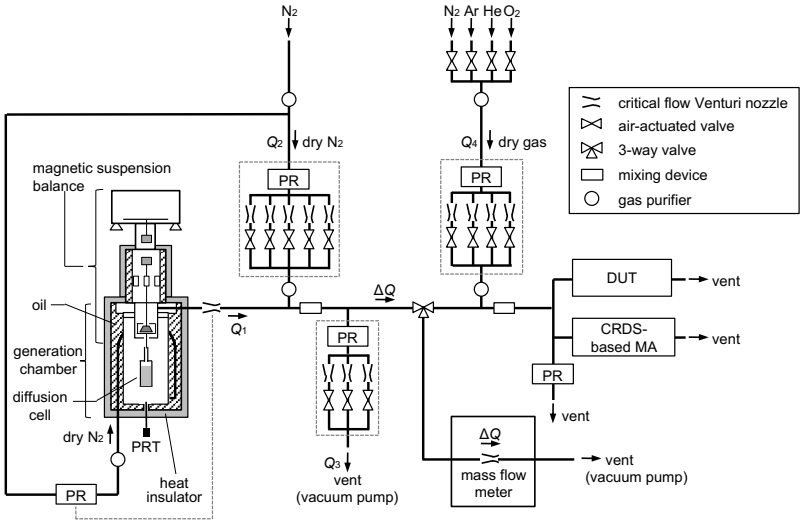

Fig.1. Schematic of the Multi-gas Trace-moisture Generator

References

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Development of a High-Pressure Dew/Frost-Point Calibration Facility at NIST

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A humidity generating facility for calibrating dew/frost-point hygrometers at pressures from 0.1 MPa to 7 MPa and at temperatures from 0 °C to 85 °C is being developed at NIST. The generator is an adaption of a research facility previously created for measuring the water-vapor enhancement factor in various gases over this pressure range [1]. The generator consists of a heat exchanger and two saturators (a pre-saturator and a final saturator) in series with each other, through which the gas flows with a rate of approximately 4 standard liters per minute. The heat exchanger and saturators, which are designed to withstand pressures up to 11 MPa, are immersed in a single commercial temperature-controlled bath. Each saturator contains a cylindrical cavity (with a vertical axis) of volume 240 mL, with approximately 120 mL of distilled water inside it. The gas flows through a set of circularly-concentric channels as it passes through the cavity. The gas used for the calibration originates from a commercial cylinder and is dry before entering the generator. The pressure of the gas inside the final saturator is kept constant to within 0.01% using a commercial pressure controller and is measured with a commercial pressure gauge. The temperature of the gas inside the final saturator is kept constant to within 8 mK and is measured with a platinum resistance thermometer. Customer hygrometers will be attached to the output of the final saturator. When used in single-pressure mode (hygrometer pressure is at saturator pressure), the dew/frost point uncertainty will be less than 30 mK. The new calibration service is expected to serve customers in the military, compressor, and compressed natural gas industries.

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New BEV / E+E Elektronik High Pressure Dew Point Generator - Design and Proof of Concept

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The current low frost point generation setup from E+E/BEV [1] exhibits a working temperature range from - 90 °C frost point up to + 20 °C dew point between atmospheric pressure and 10 MPa.

Our new setup is based on the saturator concept of the existing generator and has been designed as a single pass generator able to cover a range from -110 °C frost point up to 90 °C dewpoint in a single system due to the use of an external thermostat. The saturator has been designed for a working pressure up to 30 MPa. We thus extended the operating range of our setup by a factor of three in the pressure range, increasing the applicability of the system. Furthermore, the operability has been simplified, and the maintenance workload has been significantly reduced without any loss in accuracy. Operation mode will be primarily as one-pressure generator, but it can also be used as two-pressure generator.

Besides dew point measurements in so called air gases such as nitrogen, synthetic air or CO_2 free standard air, the need for measurements in non-air gases (NAG), for example SF_6, CH_4, H_2, CO_2, and gas mixtures such as natural gas has increased significantly in the last years. For example, the dew point must be monitored in high voltage switchgears to prevent condensation in isolation gases. For correct and accurate measurements in NAG's, fundamental thermodynamic properties such as enhancement factors must be known for the corresponding gas. In another work we report the possibility to determine enhancement factors in NAG's (for example in carbon dioxide). The design of the new setup aims to allow the determination of enhancement factors at higher pressures and lower temperatures.

Currently, the accuracy of the setup has been verified in the range from -75 °C frost point up to 20 °C dew point temperature at a pressure range from atmospheric pressure up to 1 MPa We aim to verify the full operating range of -110°C to 90°C in the near future.

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Uncertainty in trace moisture measurements by adsorption/desorption phenomena

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Importance of trace moisture generation and measurements has increased in past years. To tackle metrology challenges in the trace moisture region PrometH2O project was launched. [1]

Uncertainty analyses for metrological humidity generators typically includes uncertainty source of adsorption/desorption [e.g. 2-5]. This uncertainty source, in practice, describes how much tubing and instrumentation between the humidity generator and the device under calibration contributes to the calibration uncertainty. Similarly, the same kind of uncertainty source is valid when a sampling-based humidity measurement instruments are used. And typically, at uncontrolled environments, e.g. in field measurements, this source of uncertainty is more significant. Within this work, the adsorption/desorption is studied through experimental measurements with the most common type of sampling tube i.e. electropolished 314L stainless steel tube.

Amerio et al. noticed that water vapor concentration and pressure influence stabilization time [6]. In this work, measurements were carried out at changing temperatures from 20 °C to 30 °C and at different pressures in range of 1000 kPa and 1300 kPa and flow rates from 0.5 l/min to 2 l/min demonstrating real life sampling lines. The simplified experimental measurement set-up is described in Fig. 1.

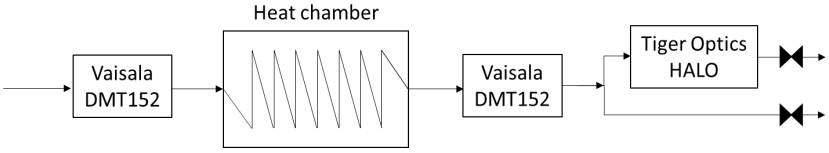

Figure 1 Simplified measurement set-up. Unstable temperature of heat chamber causes adsorption or desorption. Trace moisture levels are measured by Vaisala's DMT152 transmitters before and after a heat chamber along with a HALO from Tiger Optics.

Outcomes of the measurements indicate that uncontrolled sampling tube temperature contributes significantly to trace moisture measurements uncertainty. The measurement results also agree with earlier studies in respect of pressure and trace moisture level effects on adsorption/desorption.

Funding

This project (EMPIR 20IND06 PROMETH2O) has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.

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Lunch Session B-C

Recollections from the era of the 6th and 7th Temperature Symposia
Peter P. M. Steur (Istituto Nazionale di Ricerca Metrologica, Italy)

Recollections from the era of the 6th and 7th Temperature Symposia

Peter P.M. Steur [1]
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The author, now retired since five years and attending probably his last symposium, provides his personal impressions on how it was to work in thermometry in the nearly 10-year period embracing the 6th and 7th Temperature Symposia. These experiences are based primarily on his participation in both of those events and his professional experience conducting research in two well-known institutes in Europe. Specifically, he will draw from a four-year doctoral period at the Kamerlingh Onnes Laboratory in Leiden, The Netherlands, during the years 1979-1985, but also from his early years at the Istituto di Metrologia "G. Colonnetti" in Torino, Italy (now Istituto Nazionale di Ricerca Metrologica), from 1986-1992, where he proceeded with his career until his retirement. The subjects touched upon are the following: 1) Hiring personnel and Financing research; 2) Performing measurements in the lab, the available equipment at the time and choices of wiring; 3) Use of cryogenic liquids (helium, hydrogen and nitrogen); 4) Data elaboration using a data terminal connected to an external mainframe; 5) Literature searching and retrieving; 6) Writing a publication (on paper and typewritten); 7) Communication with international peers; 8) Presenting at the ITS6 and ITS7 (using overhead transparencies and slides). The account will contrast the past and the present and will be interspersed with a few anecdotes.

Plenary Session C: Frontiers in Temperature Measurement

The challenge for micro-nano meter scale thermometry using NV centers in diamond
Xiao-Juan Feng, Li Xing,Jin-Tao Zhang, Zheng Wang, Ke-Chen Ouyang
Invited

Themal MagIC: 3D thermal imaging and control with magnetic nano-objects
Thinh Q. Bui, Samuel D. Oberdick, Frank M. Abel, Mark-Alexander Henn, Adam J. Biacchi, Klaus N. Quelhas, Thomas Cleveland, Yanxin Liu, Michael J. Donahue, Cindi L. Dennis, Angela R. Hight Walker, Weston L. Tew, Solomon I. Woods
Invited

Invited

The challenge for micro-nano meter scale thermometry using NV centers in diamond

Xiao-Juan Feng[1], Li Xing[1], Jin-Tao Zhang[1], Zheng Wang[1,2], Ke-Chen Ouyang[1,2]
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The temperature measurement in micro-nano meter scale is important in some areas such as the biosome observation and chip manufacturing. The most commonly used traditional techniques such as thermocouples or infrared radiation methods were limited by its spatial or temperature resolutions. Recently, various optical techniques such as fluorescence, quantum dot, nitrogen-vacancy (NV) centers in diamond and thermal-magnetic nano particles have been developed [1]. The typical spatial and temperature resolutions for these methods is showed in Fig.1. The temperature measurement method which needs an external field excitation or regulation could be called active temperature measurement method. Because these techniques are usually with a temperature sensing element which could achieve a high accuracy and have no lead in the measurement, they are contact and non-contact hybrid temperature measurement method. The ultra-high spatial and temperature resolution development of such methods promotes a bright application prospect. Our present research showed that the experiences in temperature metrology could help to accelerate the practical application of the new techniques. The NV centers in diamond thermometer is based on the measurement of the zero-field splitting parameter (*D*) generated by spin-spin interaction between two unpaired electrons, as showed in Fig. 2. We reviewed the progress in three aspects which is crucial for its use. Firstly, the temperature sensitive characteristics of the diamond sensors may vary depending on different manufacturing procedures, impurities and heat-treat, so the investigation on the standard diamond sensors which showed similar *D-T* relationship is necessary. Secondly, the exciting laser and regulating microwave could bring additional heat to the diamond sensors and to the object to be measured. Usually, the higher the power of the laser and the microwave, the higher signal-to-noise ratio (*S*/*N*), so it is important to obtain an optimized power between the self-heating and the *S*/*N*. Finally, as a secondary temperature method, the *D-T* calibration method is important. A calibration apparatus with homogeneous and stable thermostatic system and reliable reference temperature is needed.

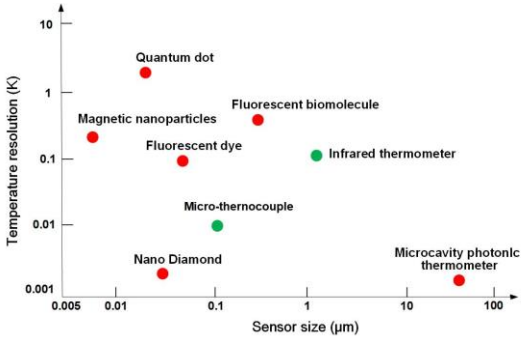

Fig. 1. The resolution for different methods

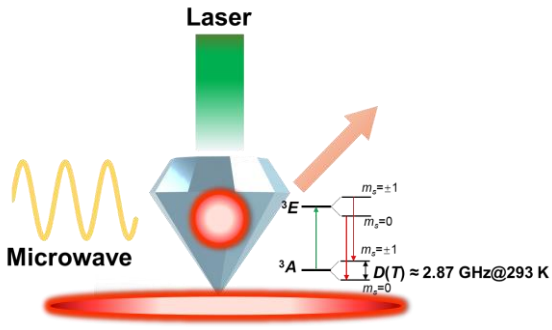

Fig.2. The schematic for NV in diamond thermometer

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Invited

Thermal MagIC: 3D thermal imaging and control with magnetic nano-objects

Thinh Q. Bui[1], Samuel D. Oberdick[3,4], Frank M. Abel[1], Mark-Alexander Henn[1,2], Adam J. Biacchi[1], Klaus N. Quelhas[1,6], Thomas Cleveland[1,5], Yanxin Liu[2,5], Michael J. Donahue[1], Cindi L. Dennis[1], Angela R. Hight Walker[1], Weston L. Tew[1], Solomon I. Woods[1]

[1]NIST, Gaithersburg, MD USA; [2]University of Maryland, College Park, MD, USA; [3]NIST, Boulder, CO, USA; [4]University of Colorado, Boulder, CO, USA; [5]IBBR, Rockville, MD USA; [6]Inmetro, Rio de Janeiro, Brazil

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The development of SI-traceable, embedded or immersed temperature sensors with remote readout, especially where measurement probes or optical access are inherently not feasible, remains a fundamental challenge. I will introduce the development of a recent NIST program – Thermal MagIC, or **Thermal** **Mag**netic **I**maging and **C**ontrol – as a new platform for high precision (δT ~ 10 mK) remote temperature measurement, 3D imaging, and control over a broad temperature range of 200 K to 400 K. Thermal MagIC is enabled by (1) engineered magnetic nanoparticles with high magnetic moments to serve as *in situ* sensors and (2) magnetic particle imaging (MPI) instrumentation [1] for non-optical and remote nanoparticle detection and control using AC magnetic fields.

3D thermal magnetic particle imaging (Fig. 1) and control rely on using strong AC (sinusoidal) magnetic fields to drive magnetic nanoparticles into saturation, resulting in a nonlinear magnetization response represented by a rich harmonic spectrum in the frequency domain. A magnetic nanoparticle thermometer is realized by measurement of the change in magnetization as a function of temperature [2]. I will discuss recent advances in achieving a new paradigm for magnetic nanoparticles as *tunable*, *ultrasensitive* tracers, whose magnetic response and thermosensitivity can be dramatically altered by affecting fundamental interparticle interactions and dynamics. Our engineered nanoparticles display a ~100x thermosensitivity enhancement compared to the state-of-the-art commercial samples (Fig. 2).

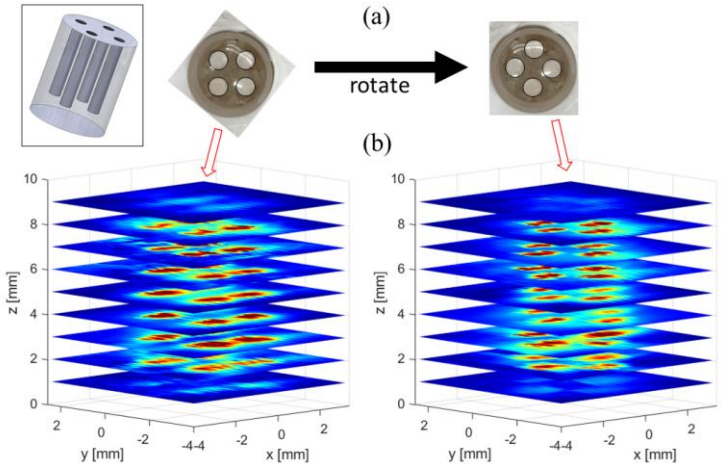

Figure 1: 3D MPI image (b) of magnetic nanoparticles embedded in a 4 channel glass phantom (a).

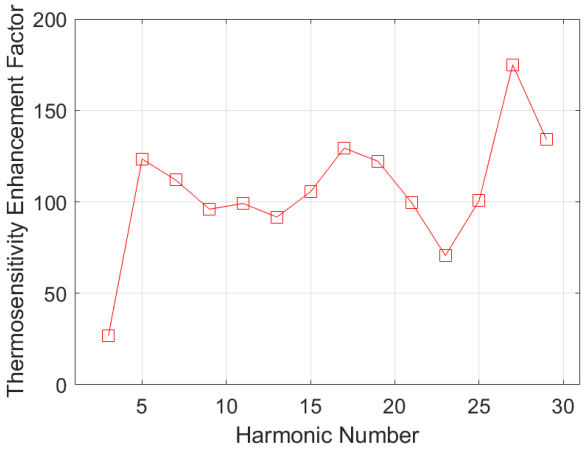

Figure 2: Thermosensitivity enhancement of engineered nanoparticles relative to a commercial sample.

References

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Parallel Session D1: Realizing the Redefined Kelvin (Real-K) I

Realizing the redefined kelvin: Extending the life of the ITS-90
Jonathan Pearce (NPL, United Kingdom (Great Britain)); Richard Rusby and Radka Veltcheva (National Physical Laboratory, United Kingdom (Great Britain)); Dolores Del Campo (CEM, Spain); Carmen Garcia Izquierdo (Centro Español de Metrología, Spain); Andrea Merlone (INRiM, Italy); Graziano Coppa (Istituto Nazionale di Ricerca Metrologica, Italy); Liliana Eusebio (IPQ, Portugal); Jovan Bojkovski (MIRS/UL-FE/LMK, Slovenia); Vincencij Žužek (University of Ljubljana, Slovenia); Fernando Sparasci (Laboratoire Commun de Métrologie LNE-Cnam, France); Peter Pavlasek (Slovak Institute of Metrology, Slovakia); Murat Kalemci (TUBITAK UME, Turkey); Ali Uytun (TUBITAK-UME National Metrology Institute, Turkey); Andrea Peruzzi (National Research Council, Canada); Aleksandra Kowal (Instytut Niskich Temperatur i Badan Strukturalnych, Poland)

Realising the redefined kelvin: Facilitating primary gas thermometry
Roberto Gavioso (INRiM, Italy); Christof Gaiser (PTB, Germany); Giovanni Garberoglio (European Centre for Theoretical Studies in Nuclear Physics and Related Areas, Italy); Christian Guenz (PTB, Germany); Robert Hellmann (Helmut Schmidt University, Germany); Bogumil Jeziorski and Michal Lesiuk (University of Warsaw, Poland); Daniele Madonna Ripa (INRiM, Italy); Karsten Meier (Helmut-Schmidt University, Germany); Robin Underwood (NPL, United Kingdom (Great Britain)); Graham Machin (National Physical Laboratory, United Kingdom (Great Britain))

Realising the redefined kelvin: Realisation and dissemination of the kelvin below 25 K
Alexander Kirste and Jost Engert (Physikalisch-Technische Bundesanstalt (PTB), Germany); Jukka Pekola (Low Temperature Laboratory, Aalto University, Finland); Joonas Peltonen (Aalto University, Finland); Shahin Tabandeh (VTT-MIKES, Finland); Laurent Pitre (LNE-Cnam, France); Fernando Sparasci (Laboratoire Commun de Métrologie LNE-Cnam, France)

Realizing the redefined kelvin: thermodynamic temperatures of Fe-C, Pd-C, Ru-C and WC-C for the mise-en-pratique of the kelvin up to 3020 K
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Realizing the redefined kelvin: Extending the life of the ITS-90

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Following the redefinition of the kelvin [1,2], the user is presented with a more nuanced traceability choice through the *mise en pratique* for the definition of the kelvin (MeP-K-19) [3]. Here we describe research to address several present and potential shortcomings with the current main dissemination route, namely using the International Temperature Scale of 1990 (ITS-90) [4]. The ITS-90 has served the global temperature measurement community well, providing reliable, low uncertainty traceability for over 30 years. However, there are some potentially life-limiting issues for the ITS-90. Among these are the impact of the main types (1 and 3) of non-uniqueness which currently limit the uncertainties achievable with the ITS-90, and the need to identify a possible alternative to the mercury triple point (a key fixed point of the ITS-90) whose use could be banned by an international treaty [5]. Progress in addressing these problems will be described through:

- New determinations of Type 3 non-uniqueness have been undertaken in the range –189 °C to 156 °C and between 660.323 °C and 961.78 °C;
- A comprehensive evaluation of Type 1 non-uniqueness on a large number of Standard Platinum Resistance Thermometers (SPRTs) across multiple regions;
- New designs of CO_2 and SF_6 cells for use with long-stem SPRTs. These have been improved by using purer gases and more stable and uniform temperature-controlled baths, and by the development of a flexible set-up that can accommodate both capsule and long-stem SPRTs. The effect of replacing mercury on the ITS-90 interpolating equations and uncertainty propagation is also being investigated.

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Facilitating primary gas thermometry

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We review the progress in the calculation and the experimental determination of the thermophysical properties of monatomic gases, as achieved in the context of the EMPIR research project "Realizing the Redefined Kelvin" (Real-K)[1] [1], and discuss how this progress will lead to improved, simplified primary gas thermometry methods with increased accuracy over extended temperature intervals.

Most notable theoretical advances include refined calculations of the interatomic two- and three-body potentials of helium [2] and neon [3], taking the accuracy of the calculation of the thermodynamic and transport properties of these gases beyond that which can be obtained by the most refined experiments. As such, both He and Ne may be considered *known* reference substances, with negligible uncertainty contributions to the overall uncertainty of gas primary thermometry and other applications of fluid metrology.

Several experimental measurements of thermodynamic properties of monatomic gases have been also recently obtained, and examined in view of their consistency with theoretical predictions. These include permittivity, refractive index and speed of sound measurements of He, Ne and Ar covering an overall wide range of temperature (between 10 K and 420 K) and pressure (up to 100 MPa). Among these experiments were simplified versions of primary gas thermometers, contributing new estimates [4] of the differences ($T-T_{90}$) between the thermodynamic temperature T and its approximation T_{90} on the International Temperature Scale of 1990 (ITS-90). Here, we discuss the achieved performance of these methods and techniques and the future perspective of their improvement.

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Realising the redefined kelvin: Realisation and dissemination of the kelvin below 25 K

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With the redefinition of the kelvin in May 2019 and the new *mise en pratique* for the definition of the kelvin (*MeP*-K-19) [1], the realisation of the kelvin is no longer exclusively confined to the International Temperature Scales (ITS-90, PLTS-2000). Although traceability to these defined temperatures scales has not changed, primary thermometry, that is measuring thermodynamic temperatures directly, has become possible as an alternative method. For that purpose, different primary thermometers that were developed and used in preceding EMPIR projects InK [2] and InK2 [3] have been optimized and extended in their operation range in the current EMPIR project Real-K[1] [4] to cover, at least partly, the temperature range from 1 K to 25 K. The primary magnetic field fluctuation thermometer (pMFFT) [5], a SQUID-based Johnson noise thermometer that is primarily used in the ultralow temperature regime, can be applied up to 6 K. The Coulomb blockade thermometer (CBT) [6], which is also able to measure temperatures down to a few millikelvin, was adapted to cover the range from below 1 K up to 25 K. The acoustic gas thermometer (AGT) [7], which was previously used in the temperature range 5 K to 200 K, was operated between 6 K and 25 K in a new version as fast-AGT, which combines relative primary measurements at a single pressure with the conventional AGT as absolute primary thermometer to provide a reference.

We will present details of these three primary thermometers as well as validation measurements that have been performed. Besides comparison with the ITS-90 at various arbitrary temperatures, two reference points served as highly stable and well characterized references. The pMFFT was checked at the superfluid lambda transition in ^{4}He (λ-point) at 2.1768 K, whereas the fast-AGT was checked at the Ne triple point at 24.5561 K. Applying the pMFFT, we demonstrated a smooth overlap between the PLTS-2000 range below 1 K and the ITS-90 range above 1 K. To conclude, the investigated primary thermometers, although quite different in nature and construction, proved to be very practical alternatives to the established thermometric methods of the ITS-90 in the range below 25 K by showing relative deviations from ITS-90 from a few 10^{-5} (AGT) to some tenth of percent (pMFFT, CBT).

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Realizing the redefined kelvin: thermodynamic temperatures of Fe-C, Pd-C, Ru-C and WC-C for the mise-en-pratique of the kelvin up to 3020 K

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The *Mise-en-Pratique* for the definition of the kelvin at high temperatures has opened the possibility of disseminating thermodynamic temperature through relative primary radiometry mediated through high-temperature fixed points (HTFPs). The thermodynamic temperatures of Co-C, Pt-C and Re-C [1] were determined under the auspices of the Euramet joint research project InK [2]. Here we report on efforts to determine the thermodynamic temperature of the phase transition of four more HTFPs, namely, Fe-C ~1426 K, Pd-C ~1765 K, Ru-C ~2227 K and WC-C ~3020 K as part of the European research project Real-K [3].

During this three-year project (ending April 2023) participants from nine countries (some beyond Europe) have contributed to this endeavour by a) supplying HTFP cells b) selecting the best cells for thermodynamic temperature assignment c) performing direct or relative thermodynamic temperature measurements on the circulating cells and d) comparing the cells for drift analysis.

This presentation gives an overview of the experimental activities performed during the project and summarizes the results of the thermodynamic temperature assignment. In fig1, the reported provisional thermodynamic temperatures of the point of inflection (poi) are shown for the WC-C point. The agreement between the participants is noticeably good and the weighted mean temperature has been determined collectively with an expanded uncertainty of 0.25 K thanks to the independent determinations at 6 different institutes.

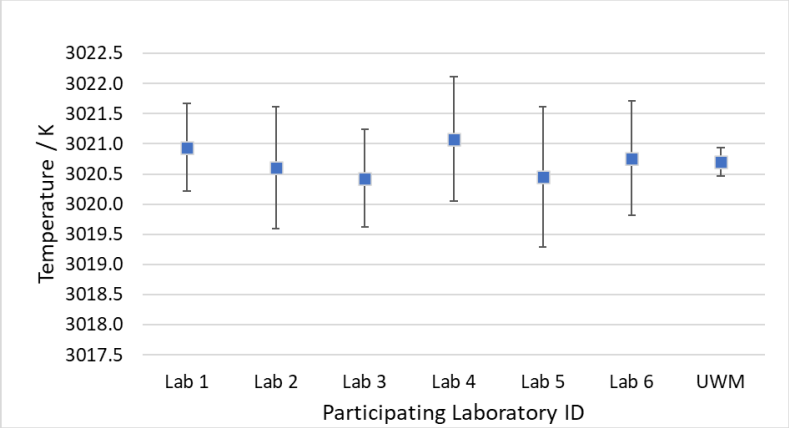

Fig. 1. Reported point-of-inflection thermodynamic temperatures and uncertainties (k=2) from participating laboratories, compared to the uncertainty-weighted mean (UWM) with its uncertainty (including thermal effects)

Finally, after two decades of research and cooperation a series of seven HTFPs with assigned thermodynamic temperatures will soon be available for the realization of the kelvin and its dissemination.

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Parallel Session D2: Radiation Thermometry - Emissivity

Visualizing emissivity with short wave infrared hyperspectral thermal imaging
Matthew MJ Davies and Emilios Leonidas (University of Sheffield, United Kingdom (Great Britain)); Matthew J Hobbs (The University of Sheffield, United Kingdom (Great Britain)); Jon R Willmott (University of Sheffield, United Kingdom (Great Britain))

Accurate Emissivity Characterization of Metals from Near Infrared (NIR) to Mid Wave Infrared (MWIR)
Benedict EG Davies, Matthew MJ Davies and Jon R Willmott (University of Sheffield, United Kingdom (Great Britain)); Matthew J Hobbs (The University of Sheffield, United Kingdom (Great Britain))

Normal spectral emissivity measurement of graphite above 1000°C by modified integral blackbody method via adjusting sample movement state
Luge Sun (National Institute of Metrology, China); Xuyao Song (Beijing Aeronautical Technology Research Center, China); Wei Dong (National Institute of Metrology, China); Baolin An, Yunlong Zhao and Zundong Yuan (National Institute of Metrology, China); Xiaofeng Lu (National Institute of Metrology, China & NIM, China); Tiejun Wang (National Institute of Metrology, China)

Visualizing emissivity with short wave infrared hyperspectral thermal imaging

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Emissivity is the efficiency with which an object emits thermal radiation. It is a dimensionless quantity that varies between 0 (a perfect mirror) and 1 (a perfect absorber). Optical thermometry relates the intensity of this radiation to temperature according to a calibration performed with an approximate blackbody, usually a heated cavity.

Emissivity presents a considerable obstacle to optical thermometry in part due to its dependence on emitted wavelength, material and surface finish of the measurand [1]. Thermal imaging is used for temperature measurement because it maps the scene to enable interpretation of surface finishes and object geometries. This offers context to temperature measurements that are potentially unavailable to single point radiometers [2]. Hyperspectral imaging allows direct determination of spectral radiance over a continuous waveband while providing the advantages of spatially distributed radiance measurements [3].

We have developed a short wave infrared hyperspectral imaging camera to measure spatially distributed spectra from a variety of heated metal samples. This enables measurement of spectral radiance for varying materials and surface finishes over a continuous spectral range of 0.95 to 1.43 µm. This radiance is used to infer the spectral emissivity within this range. We also investigate multi-ratio thermal imaging as a means of emissivity independent temperature measurement and spectral emissivity determination.

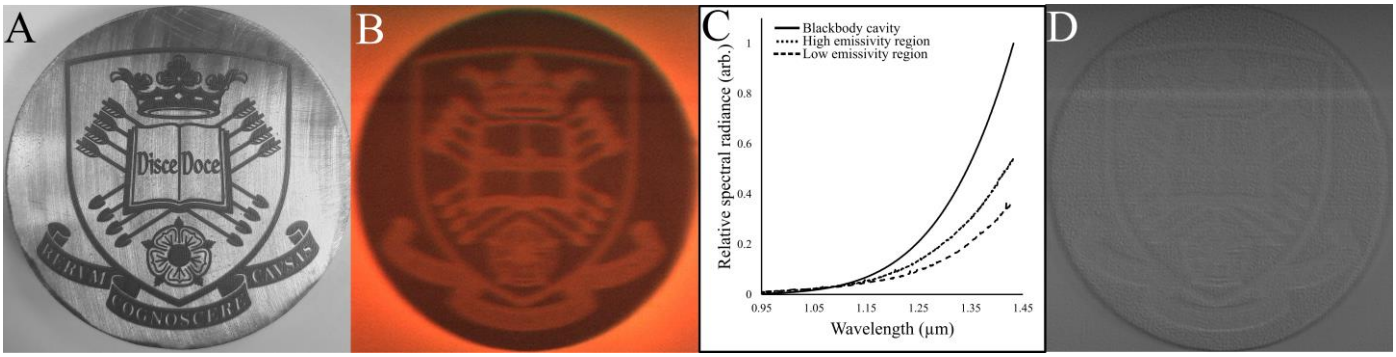

Figure 1 (A) A photograph of a laser etched target; (B) A pseudo RGB image of the target heated to 378 °C; (C) A plot of relative spectral radiance against wavelength; (D) A ratio of the images corresponding to 1.33 and 1.43 µm.

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Accurate Emissivity Characterization of Metals from Near Infrared (NIR) to Mid Wave Infrared (MWIR)

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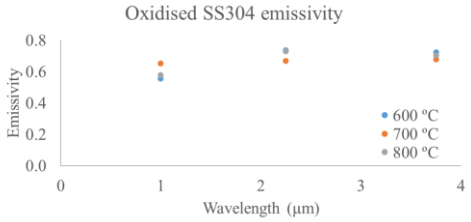
Accurate measurement of temperature is critical within process manufacture; such measurements can only be achieved through the use of infrared radiation thermometry if the material's emissivity is known. It is also paramount to know the values of emissivity for materials from which heat exchangers are built; without this, accurate thermal models cannot be created, and models cannot be verified by comparison to the real-world process. Accurate knowledge of emissivity across the full spectral range is required for incorporation into such thermal models because emissivity changes as a function of wavelength as well as temperature. There is a dearth of testing facilities that can offer accurate emissivity measurements over such a large wavelength and temperature ranges necessary for the creation of such models.

We have directly addressed the need for the accurate quantification of emissivity as a function of wavelength. By combining a split-tube furnace [1] with bespoke, calibrated radiometers, we are able to accurately measure the emissivity of materials from the near infrared through to the mid wave infrared at discrete wavelength bands. Our new approach to spectral emissivity characterization enables measurement of emissivity at specific wavelengths through incorporation of desired bandpass filters. The system can also be extended into the long wave infrared, with the potential to measure emissivity at ambient temperatures or below through the use of cooled photodetector-based radiometers.

In this paper, we measure the emissivity of SS304 as a function of wavelength and temperature. We demonstrate the measurement of emissivity at discrete wavelengths of 1, 1.5, 2.25, 3.75 and 4.75 um, and at temperatures of 200 to up 1100 °C. A full uncertainty budget has been created for the measurement setup to ensure traceability of error in the measurement.



Wavelength / µm	600K	700K	800K
1.00	0.555	0.653	0.579
2.25	0.737	0.668	0.731
3.75	0.725	0.679	0.703

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Normal spectral emissivity measurement of graphite above 1000℃ by modified integral blackbody method via adjusting sample movement state

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The integrated blackbody method is described as a new method of high-temperature emissivity measurement that does not require measurement of the sample surface true temperature, and some studies of this method are published by several authorities. The original study is used as the basis, and after extensive experiments, the temperature drop of the sample surface is considered a non-ideal factor, and the emissivity measurement results are seriously affected. However, the sample temperature drop is influenced by the sample movement state, so the sample push-out process temperature drop is discussed, relying on a theoretical model of the sample surface temperature drop to be developed, as well as changing the sample push-out state experiment.

In this paper, from the perspective of reducing measurement uncertainty and improving measurement accuracy, The theoretical model of the sample surface temperature drop in the integrated blackbody emissivity measurement method is presented, relying on the integrated blackbody cavity temperature field measurement experiment, the assumption of the heat transfer model for the sample movement state, and the finite-element discretization idea. The validation method of changing the sample push-out time to extrapolating 0 temperature drop is investigated, and the effect of the sample push-out state on the emissivity measurement results is discussed.

The infrared spectral emissivity of graphite samples in the (3~14) μm spectral range is measured at temperatures of 1300° C and compared with published measurements. The detailed measurement results and details are reported in the paper.

Parallel Session D3: Platinum Resistance Thermometry

On the analysis of non-standard platinum resistance thermometers
Martin J de Groot (MartinDeGroot Consultancy & Kelvin-Trainingen, The Netherlands); Jovan Bojkovski (MIRS/UL-FE/LMK, Slovenia); Vincencij Žužek (University of Ljubljana, Slovenia)

Sensitivity of Type 1 Non-uniqueness (Subrange Inconsistency) to Propagated Measurement Error in SPRT Interpolations above 273.16 K
Richard Rusby (National Physical Laboratory, United Kingdom (Great Britain)); Jonathan Pearce (NPL, United Kingdom (Great Britain))

Full-range Interpolations for Long-Stem Standard Platinum Resistance Thermometers down to the Triple Point of Argon
Richard Rusby (National Physical Laboratory, United Kingdom (Great Britain)); Jonathan Pearce (NPL, United Kingdom (Great Britain))

From ITS-90 to Thermodynamic Temperature: Hybrid SPRT Calibrations with LNE-Cnam Acoustic Gas Thermometry
Dario Imbraguglio (INRiM, Italy); Changzhao Pan (Shenzhen Institute for Quantum Science and Engineering-International Quantum Academy, China); Fernando Sparasci (Laboratoire Commun de Métrologie LNE-Cnam, France); Roberto Gavioso and Daniele Madonna Ripa (INRiM, Italy); Patrick M.C. Rourke (National Research Council Canada, Canada); Haiyang Zhang (The Technical Institute of Physics and Chemistry of the Chinese Academy of Sciences, China); Bo Gao (Technical Institute of Physics and Chemistry of the Chinese Academy of Sciences, China); Laurent Pitre (LNE-Cnam, France)

On the analysis of non-standard platinum resistance thermometers

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In the ITS-90 [1] the temperatures and functions have been defined that are to be used when calibrating standard platinum resistance thermometers that satisfy the purity required for the realization of the temperature scale. For platinum resistance thermometers that do not comply with the purity requirement the general approach is to either use Callendar-van Dusen as defined in IEC 60571 and OIML 84 [2,3,4] or use the ITS-90 procedure nonetheless. The applicability of Callendar van Dusen is limited to 0.1 °C, in particular to temperatures below 0 °C [4,5].
Alternative approaches to overcome the limited value of the Callendar van Dusen equation, were described by Marcarino e.a. [5,6] who proposed a high order improvement of CVD only fitting the low order coefficients. Fernicola e.a.[7] applied least squares techniques to calculate ITS-90 deviation equations. Connolly[8] used low order polynomials to R(t) and t(W-1). One of us [9] fitted low order Chebyshev equations to the deviation from the ITS-90 reference function.
With improved calibration techniques and improved PRT production over the years, comparison calibrations allow uncertainties of the order of 3 mK to be achieved in the temperature range from -100 °C to 300 °C.
This paper will reflect on the different approaches used to calibrate non-standard PRT's and compares the residuals of calibration from these approaches.
In order to reduce cost and time of calibration, there is pressure on calibration laboratories to perform "single point calibrations" of thermometers, in particular when these sensors are used for monitoring purposes. VIM [10] definition 2.39 on calibration states "in a second step, uses this information (from step one) to establish a relation for obtaining a measurement result from an indication". When issuing a certificate on the basis of the single temperature measured, the calibration lab will have to consider methods to define the range validity with an equally valid uncertainty. The paper will discuss this on the basis of the thermometer data.

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Sensitivity of Type 1 Non-uniqueness (Subrange Inconsistency) to Propagated Measurement Error in SPRT Interpolations above 273.16 K

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This paper documents the sensitivity of Type 1 non-uniqueness (subrange inconsistency, SRI) to errors in the measurements of Standard Platinum Resistance Thermometers (SPRTs) at the fixed points of the International Temperature Scale of 1990, ITS-90, specifically on pairs of interpolations from the triple point of water (TPW, 273.16 K) up to the freezing points of zinc (FP Zn, 692.677 K) and aluminum (FP Al, 933.473 K). The interpolations are calculated using the equations specified in the ITS-90 and some potential alternatives to them.

The sensitivity to errors (or uncertainties) in the various subranges have been extensively documented, usually for unit (1 mK) errors at the fixed points, and in this paper we present curves showing the combined propagation of these errors in the SRI. This is done for the more significant pairs of subranges, namely for the TPW to FP Zn relative to the TPW to FP Al, designated SRI[Al: Zn], and TPW to FP Sn relative to the TPW to FP Zn, SRI[Zn: Sn]. The figures show clearly which of the fixed points have the largest effect. We also present some alternative, non-specified interpolations, in which FP In is included and least-squares interpolations are used.

The paper then considers the origins of SRI, as measured, from 5 possible sources:

1. Incompatibilities between the reference resistance ratios, Wr, in the ITS-90,
2. Differences caused by the interpolation equations specified,
3. Differences between the samples of platinum wire used in the construction of the SPRTs
4. Changes in SPRT characteristics during the calibration process,
5. Propagation of errors in the measurement of the SPRT at the fixed points.

The first two are intrinsic to the scale itself, the third is inherent in SPRT manufacture, and is the effect of Type 3 non-uniqueness on the SRI. The fourth may be mitigated by careful manufacture and procedure, but is unpredictable, while the fifth can also be reduced by careful experimentation, but cannot be eliminated.

These are briefly discussed, but it is clear that the last is the dominant source of the ‘apparent’ SRI. Peruzzi et al recently published a survey of the SRI for all 16 pairs of the 7 subranges of the ITS-90 from the triple point of argon (TP Ar, 83.8058 K) to the FP Al, using data for SPRTs from recent key comparisons and some additional NMI data. This showed considerable dispersion in the curves for the different SPRTs, which they found could largely be due to the propagation of uncertainties in the data (Point 5): the expanded uncertainties would cover all but a few outlying SPRTs, which could easily be the result of SPRT instability (Point 4). Thus, if SRI is a meaningful quantity, caused by the first three sources above rather than as an artefact of the calibration, it is not determined simply by taking the differences between SPRT interpolations. As for Type 3 non-uniqueness, we can only say that the true SRI lies somewhere within the limits of our experimental uncertainty.

Full-range Interpolations for Long-Stem Standard Platinum Resistance Thermometers down to the Triple Point of Argon

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This paper offers a possible solution to the present and potential future difficulties with the International Temperature Scale of 1990, ITS-90, regarding the triple point of mercury (TP Hg, 234.3156 K).

The TP Hg is a first-quality fixed point, which was introduced in the ITS-90 to reduce the Type 3 non-uniqueness of the scale just below the triple point of water (TPW). Unfortunately the value for the resistance ratio, W_r(Hg), and hence the temperature, was not ideally chosen, with the result that there is a mismatch between interpolations of T_{90} above and below the TPW, which suggest that T_{90}(Hg) is too high by ~1 mK.

While this has not been a practical issue outside NMIs, a more serious problem may be the growing concerns over the use of mercury, even in well-controlled scientific laboratories. If, as may happen, the use of mercury is banned, it will be necessary to amend the ITS-90. Various alternative fixed points are being investigated, and the point favored for cryogenic thermometry is the TP xenon (T_{90} ~160 K), because it is approximately mid-way between the TP Ar and TPW. However, it is below the temperature at which liquid baths can be operated, so presenting a barrier to using xenon cells for the calibration of long-stem Standard Platinum Resistance Thermometers.

To overcome this, we propose that full-range interpolations should be used, without any replacement for the TP Hg, from TP Ar to the maximum temperature desired, using the existing ITS-90 equations with an extra term. The fixed points TP Ar, TPW, the freezing points of Sn, Zn and Al, are spaced at intervals of about 200 K, so quadratic, cubic or quartic interpolations from TP Ar to progressively higher temperatures are well-behaved, with good consistency between them. The consistency with respect to the ITS-90 above TPW, which would continue in use, is also generally good.

We have investigated such interpolations analytically and show that errors or uncertainties propagate with no amplification except above FP Zn. We also show that the sensitivity to error of Type 1 non-uniqueness (Subrange Inconsistency, SRI) is comparable with, or better than, that in the present ITS-90. Finally, we show comparisons between these interpolations and the ITS-90, using data from CCT Key Comparison K9. For Ar to Sn, a bias of ~1 mK is found in the differences above TPW, most likely because the ITS-90 includes the FP In, but for Ar to Zn the differences are all less than 0.5 mK. Below TPW the comparisons show clearly the problem with the TP Hg which we are trying to overcome.

We conclude that, while the ITS-90 subranges may have equal status, they do not have equal uncertainties. The most consistent set of interpolations will be those from TP Ar or TPW, as appropriate, and work up through FP Sn, Zn and Al, as far as needed. Additional points such as TP Hg (substitute), the gallium point and FP In will still be needed for specific purposes.

From ITS-90 to Thermodynamic Temperature: Hybrid SPRT Calibrations with LNE-Cnam Acoustic Gas Thermometry

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In the cryogenic temperature range between 13.8033 K and 273.16 K, eight fixed points are required by the International Temperature Scale of 1990 (ITS-90 or T_{90}) [1] to fully calibrate a standard platinum resistance thermometer (SPRT). Two of them are often no longer realized according to the prescriptions defined in the scale but by comparison with a "wire scale": they are the two temperatures close to 17 K and 20.3 K. On the other hand, some primary methods as acoustic gas thermometry (AGT) [2] are now able to measure any thermodynamic temperature T in this range with user-adjustable spacings, as shown in Fig. 1 (left).

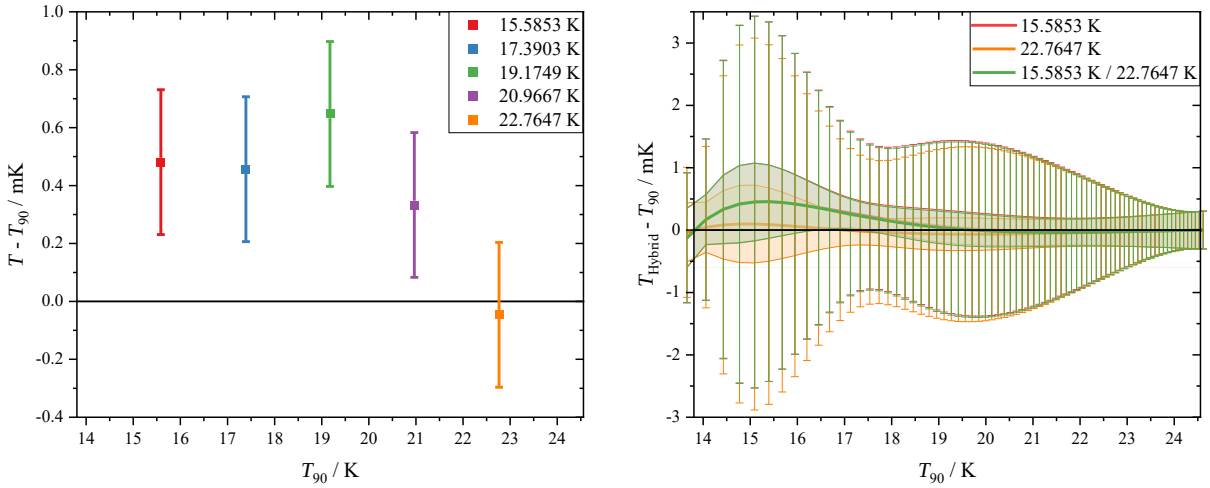

Fig. 1. Experimental determinations of T - T_{90} by AGT (left) and calculated "T_{Hybrid}"- T_{90} differences (right); in the first case, only the uncertainty contribution from AGT is considered, while in the second one, this (lines with shaded areas) is compared with that of a typical T_{90} realization (error bars).

We investigate here the suitability of "hybrid" calculations for the temperature (T_{Hybrid}) with a SPRT carrying both ITS-90 and AGT calibrations. The ITS-90 equations are applied to a modified fixed-point set, where the two mentioned ITS-90 points are replaced by (alternative) thermodynamic temperatures close to those of the original fixed-points. Several AGT points are tested as possible replacements, by substituting them in the calculation procedure of the calibration coefficients. The results (right in Fig.1) consider different scenarios, where only one or both ITS-90 points are replaced, to find the optimal combination for the difference T - T_{90} with the lowest uncertainty.

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Parallel Session D4: Photonic Thermometry

Fibre Optic-based Thermometry: evolution and development spanning five decades
Kenneth Grattan (City University London, United Kingdom (Great Britain)); Tong Sun (City University of London, United Kingdom (Great Britain)); Matthias Fabian (City, University of London, United Kingdom (Great Britain))
Invited

Photonic thermometry program at NIST: towards a new way of realizing temperature
Nikolai N Klimov and Kevin O Douglass (National Institute of Standards and Technology, USA); Tobias Herman (NIST, USA); Daniel S Barker (National Institute of Standards and Technology, USA); Ashutosh Rao (University of Maryland USA, USA); Sarah M Robinson (National Institute of Standards and Technology, USA); Thomas P. Purdy (University of Pittsburgh, USA); Zeeshan Ahmed and Michal Chojnacky (National Institute of Standards and Technology, USA)

Development of Whispering Gallery Mode Photonic Thermometer at NIM
Yijie Pan (National Institute of Metrology, China); Cheng Zhang (Beijing Institute of Technology, China); Jin Wang and Jifeng Qu (National Institute of Metrology, China); Yuning Duan (National Institute of Metrology (NIM), China)

Invited

Fibre Optic-based Thermometry: evolution and development spanning five decades

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Fiber Optic Sensors (FOS) have been developed since the late 1970s and amongst the earliest devices produced have been transducers for the measurement of temperature, particularly given its importance to industry. That period saw some of the first experiments on low-loss optical fibers being used, not for telecommunications — as had been the prime motivation for their development — but for sensor purposes and success to measure temperature in a then new and important way [1].The suite of optical fiber sensors, including those for temperature measurement, owes its development to two of the most important scientific advances made in the previous decade — the laser (1960) and the modern low-loss optical fiber (1966). In addition, the 1980s saw the first use of non-linear optical techniques for distributed temperature sensing and the success of the side-written Fiber Bragg Grating in the late 1980s opened up the potential of this important in-fiber device for quasi-distributed temperature sensors.

Research in the field has continued now for nearly five decades and the main driver of such research continues to be to produce a range optical-fiber based techniques which can be used for a variety of different sensor purposes, providing a foundation for an effective temperature measurement technology for industry and which can complete with conventional methods, especially in niche areas. It is clear that reliable measurement of temperature continues to be important for a considerable breadth of applications, including the aerospace field, oil and gas, materials and nuclear and renewable energy production, amongst many others. Temperature monitoring for combustion and in turbines play a key role in today's society and fiber optic temperature sensors enable measurements in harsh environments, for example those where high temperatures, pressures, and strong electromagnetic fields make more conventional techniques either inappropriate or difficult to use. Therein lies the recipe for the success of optical fiber sensors — in tackling successfully difficult measurement situations where conventional sensors are not well suited to use, working well in a particular environment. Fiber optic sensors are typically compact and lightweight and have successfully moved on from the initial single point sensors to offer multiple measurements from a single fiber network [2].

The development of the field over the period and the wide range of techniques and applications provides a fascinating insight, as new applications are opening up, especially for high temperature measurement [3]. All this points to the importance of a closer examination of the different techniques proposed, the way those have either gone on to success or been largely discarded and the continuing need for better temperature monitoring for a number of different industries which can be best served by using fiber optic techniques, fully exploiting on-going developments.

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Photonic thermometry program at NIST: towards a new way of realizing temperature

Nikolai N Klimov[1], Kevin O Douglass[1], Tobias K Herman[1], Daniel S Barker[1], Ashutosh Rao[1,2], Sarah M Robinson[1], Thomas P Purdy[1,3], Zeeshan Ahmed[1], Michal J Chojnacky[1]
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Reliable measurements of temperature play a crucial role in numerous aspects of modern science, technology, and everyday life ranging from medicine and Earth climate to semiconductor industry and advanced manufacturing process control. While there have been great strides in developing novel thermometry, resistance-based thermometry remains the standard method for disseminating the SI unit of temperature at the highest level of precision. The Standard Platinum Resistance Thermometer (SPRT) is the best-in-class resistance thermometer, but it has fundamental limitations in performance due to susceptibility to environmental variables such as thermal shock, mechanical stress, and humidity. Susceptibility to these effects can necessitate frequent recalibration, adding to cost and reducing productivity. The limitations of resistance thermometry, as well as the desire to reduce sensor ownership cost, have ignited a substantial interest in the development of alternative technologies such as photonics-based temperature sensors. Here we describe the Photonic Thermometry program at the National Institute of Standards and Technology (NIST) which we launched several years ago. Within this program, we are developing a new temperature measurement solution with potential to revolutionize how temperature is realized and disseminated to customers. The major difference now compared to legacy thermometry is that we are sensing photons instead of electrical resistance. One of the enabling elements of our program is an ultra-Sensitive Photonic Thermometer (SPoT) – an on-chip integrated silicon nanophotonic resonator, whose optical resonance frequency is highly sensitive to temperature variations. Our goal is to evolve SPoT into a robust, field-deployable device that is on par or better that the state-of-the-art resistance thermometer.

In this work, we describe one of the designs of SPoT thermometer, featuring a silicon photonic crystal cavity nanoresonator that has a very sharp resonant optical mode in its transmission spectra in the telecom frequency range (Fig. 1). The mode frequency shifts with temperature due to high thermo-optic coefficient of silicon and can be used to trace temperature variations with high precision. In our read-out scheme, we employ a novel offset-locking technique for reading out the resonance wavelength of the SPoT. This method provides extremely high accuracy for relative temperature changes on a short time scale (<< 1s). Our results indicated that the packaged on-chip integrated SPoT is can detect temperature fluctuations as small 2 μK over 200 ms integration time (Fig. 2). This methodology as well as other proposed methods will be discussed. We also show a benchmark comparison of SPoT thermometer to SPRT in various fixed-point cells of ITS-90, evaluating temperature resolution and repeatability.

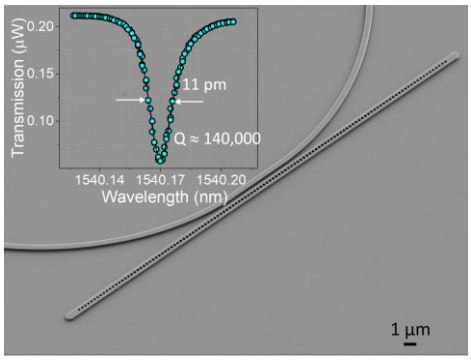

Fig 1*:* SEM image of SPoT. Insert: SPoT's optical resonance.

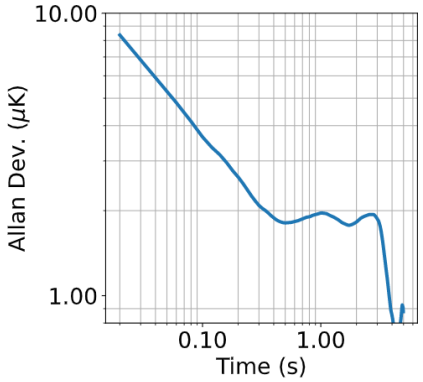

Fig. 2. Allan deviation plot of SPoT in water triple point.

Development of Whispering Gallery Mode Photonic Thermometer at NIM

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Whispering gallery mode(WGM) photonic thermometry features high physical and chemical stability, electromagnetic field immunity, and CMOS-compatible mass production capability, which is a promising temperature sensing approach for harsh environments. However, due to the large material absorption and corresponding relatively low device quality factor, WGM photonic thermometer suffers from low resolution, large self-heating, and narrow measurement range. In this report, we review the methods and results that the National Institute of Metrology, China proposed of our recent research, including 1) Fabrication and characterization of an on-chip silicon WGM ring resonator thermometer: The quality(Q) factor, temperature sensitivity, and measurement range of the packaged device reach 21400, 42 pm/K, and 150 K, respectively, and an actual-measured temperature resolution of 2.9 mK was achieved by side-of-fringe detecting method. 2) A photonic thermometer with sub-millikelvin resolution and broad temperature measurement range implemented by a simple waveguide-micro-ring Fano structure: The wavelength-temperature sensitivity was 75.3 pm/K, the intensity-temperature sensitivity at the Fano asymmetric edge was 7.49 dB/K, and the temperature resolution was 0.25 mK within 10°Cto 90°C. 3) A photonic sensor with less than millikelvin self-heating effect utilizing silicon nitride (Si_3N_4) micro-ring resonator: Taking the thermo-refractive and the Kerr effects into account and investigating thermal broadening transmission spectra under various probing powers, both the effective absorption coefficient and the thermal relaxation rate of the device were obtained. The method further predicted and experimentally proved the self-heating temperature rise could be mitigated to 245 μK. At last, the report will give an outlook of approaches for further resolution enhancement and the development of a hardware driver for WGM photonic thermometry.

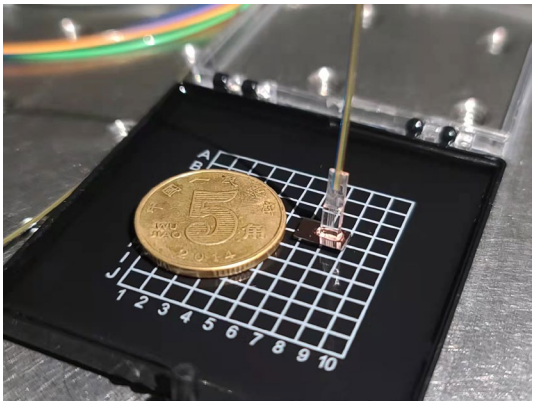

Fig.1 Packaged WGM photonic thermometer.

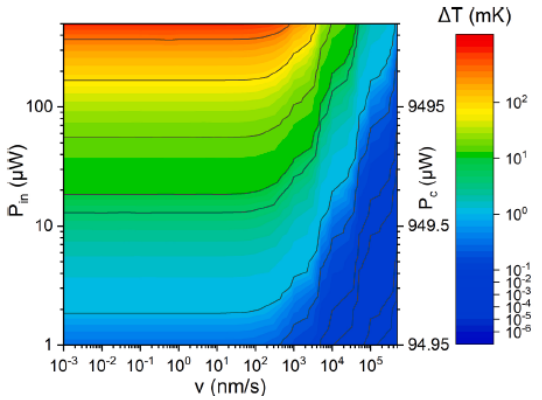

Fig.2 Prediction of the self-heating temperature rise.

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Plenary Session E: Trends in Industrial Temperature Measurement

Temperature Metrology Needs for High-Tech Industries and Critical Infrastructure
Steffen Rudtsch (Physikalisch-Technische Bundesanstalt, Germany)
Invited

Digital metrology: benefits, challenges and open questions
Louise Wright (National Physical Laboratory, United Kingdom (Great Britain))
Invited

Invited

Temperature Metrology Needs for High-Tech Industries and Critical Infrastructure

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The need to minimize the impact of energy production and consumption on the climate requires a transformation of our current energy systems away from fossil fuels and towards an efficient and flexible low-carbon system. This is associated with technological and metrological challenges and requires solutions that have to be validated and implemented in a comparatively short time. Most of these challenges are associated to the implementation of renewable energy sources who provide electrical energy intermittently instead of on demand. The resulting highly variable thermal loads require both tighter distributed and long-distance temperature monitoring within the electricity grid, in particular within transformers, along high-voltage cables, at connectors and other parts of the power network. But conventional electrical thermometers are not suitable for distributed sensing and operation close to varying magnetic fields. Further requirements are related to the urgent need for optimized heat storage systems at various temperature levels from about 0 °C up to more than 1000 °C. The operation and optimisation of these systems and the quantification of the loading state requires in particular sophisticated distributed temperature sensing.

Most industrial needs are related to efficiency requirements for energy intensive high-temperature processes like silicon purification but also quality demands due to thermal processes, e.g. the manufacturing process of single-crystal turbine blades. Other ambitious specifications are related to industrial processing of high-quality materials in specific industrial sectors, such as AMS 2750 F (Aerospace Materials Specifications). In my talk I will present promising methodologies for these and other tasks for high temperatures and discuss open questions to achieve the required Technology Readiness Level for ready-to-use solutions. Other demanding examples are industrial processes within temperature-controlled environments with millikelvin or sub-millikelvin stability and homogeneity. Finally, I will present some sector specific needs and solutions such as temperature measurements within optoelectronic circuits, fire detection in railroad tunnels or icing of high-voltage transmission lines in Nordic regions.

Invited

Digital metrology: benefits, challenges and open questions

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Digital sensors and digital measurements are already part of our world, thanks to improvements in sensor technology, data transfer and flexible computing. The increase in the volume and velocity of data from such sensors has led to changes in the way we process, analyse and visualise such data, and has created opportunities for automation, remote operation and real-time access that can cut error rates and save time across multiple industrial and societal applications. Digitalisation and cloud storage can enable data sharing across technical areas of expertise to tackle multi-disciplinary problems such as climate change and to advance scientific research more rapidly.

For the full benefits of these opportunities to be realised, the confidence in data that metrology brings must be present. A measurement result requires an associated uncertainty whether it comes from a straight line fit to data or a neural network. Traceability of measurements back to national standards is as important for digital data that has gone through a complex processing chain as it is for values reported on a paper calibration certificate.

New measurement modalities such as sensor networks and quantitative imaging that are enabled by digital technologies are generating innovative thinking around calibration, traceability and uncertainty evaluation. Digitalisation can raise questions that require metrologists to consider whether some of their fundamental approaches need to be extended to handle the new possibilities it brings. How can we guarantee that automation algorithms keep the link between quantity and unit that makes measurement results meaningful? How can we ensure that uncertainty quantification for machine learning algorithms captures all of the uncertainty sources adequately? Do realisations of the SI units at point of use reduce NMIs to digital monitoring or do they remain the highest point of truth?

Many of these questions are being driven by advances in temperature metrology in particular. Examples include Johnson noise thermometry and self-validating thermocouples. Temperature sensors with digitized output have been in widespread industrial use for several decades. The measurement of temperature is essential over a very wide range of disciplines so temperature metrologists are already familiar with the challenges and benefits of sharing data across such disciplines in a meaningful way.

This talk will discuss the benefits and risks of digital metrology, and will offer an overview of ongoing research efforts to create a digital infrastructure for metrology that ensures that digital measurements are trustworthy and traceable, and that metrology benefits from the advances that digitalisation offers.

Parallel Session F1: Non-metal Fixed Points I

Realization of the triple point of carbon dioxide at NPL
Radka Veltcheva (National Physical Laboratory, United Kingdom (Great Britain)); Rodrigo Da Silva (National Physical Laboratory - NPL, United Kingdom (Great Britain)); Jonathan Pearce (NPL, United Kingdom (Great Britain))

Capsule and Long stem SPRT calibration by low volume fixed point of Sulfur Hexafluoride (SF6)
Peter Pavlasek (Slovak Institute of Metrology, Slovakia); Lara Risegari (LNE-Cnam, France); Fernando Sparasci (Laboratoire Commun de Métrologie LNE-Cnam, France)

The different metrological performance between the two CO2 triple point cells
Yu Liang, Jintao Zhang and XiaoJuan Feng (National Institute of Metrology, China)

Evaluation of the triple point of xenon and temperature scales of SPRTs calibrated at the tripe point of xenon, carbon dioxide and sulfur hexafluoride
Yasuki Kawamura (National Institute of Advanced Industrial Science and Technology (NMIJ, AIST), Japan); Tohru Nakano (AIST, Japan); Nobuhiro Matsumoto (National Institute of Advanced Industrial Science and Technology, Japan)

Realization of the triple point of carbon dioxide at NPL

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In the temperature range from 13 K to 273.16 K the International Temperature Scale of 1990 (ITS-90) is defined by means of platinum resistance thermometers calibrated at defining fixed points and using specified interpolation procedures. Long stem Standard Platinum Resistance Thermometers (SPRTs) used in the subrange from 83.8058 K (triple point of argon) to 273.16 K (triple point of water) must be calibrated at the triple points of argon, mercury (234.3156 K) and water. The UN Minamata Convention on Mercury [1] introduced controls over a huge number of products containing mercury, which may prevent its use for scientific purposes in the future. This raises the necessity of looking for an alternative fixed point to replace the hazardous mercury. The potential candidates are xenon, sulfur hexafluoride (SF_6) and carbon dioxide (CO_2).

Most previous investigations of the performance of the CO_2 fixed point have been aimed at capsule-type platinum resistance thermometers with the realization of the cell occurring in calorimeters. [2,3]. A high purity carbon dioxide cell for use with SPRTs was designed and manufactured circa 1995 [4]. Recently, the cell was brought out of long-term storage and placed into a well-stirred oil bath for realization of the freezing and melting plateaus. Despite the long storage period the CO_2 was still present, and during the investigation process more than ten plateaus have been realized which showed reproducibility of 0.5 mK using techniques which are readily adapted to routine calibration services. The length of the plateaus was typically about 20 hours, with a temperature range of 0.5 mK or smaller. The triple point temperature realized by the cell was found to be 216.5910 K ± 0.0005 K ($k=1$) as measured by a calibrated SPRT, which is consistent with the value measured 25 years ago.

In this paper new realization techniques to improve reproducibility and reduce uncertainty are described, the determination of the triple point temperature is outlined, and the realization uncertainty is evaluated.

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Capsule and Long stem SPRT calibration by low volume fixed point of Sulfur Hexafluoride (SF_6)

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In the recent years a significant effort was invested in the development and characterization of a novel low temperature fixed point cell that would replace the currently used ITS-90 [1] defining fixed point cell of mercury (Hg). These attempts were dominantly motivated by the restriction of use of heavy metals in multiple countries. The European Union mercury regulation 2017/852 [2] can be used as an example of these restrictions. In order to have a minimal effect on the current International Temperature Scale of 1990 several materials with similar triple point temperatures were considered. These were CO_2 (216.59 K) [3, 4] and SF_6 (223.555 K) [5, 6]. In this contribution we will be focusing on the later of the two and on the performance of a low volume SF_6 with a total cell volume below 0.05 l. This cell has been specifically designed to enable simultaneous calibration of capsule and long stem type of SPRTs (Standard Platinum Resistance Thermometers) in different cooling apparatuses (cryostats, baths etc.). The conducted measurements that are going to be presented and discussed were realized in quasi-adiabatic conditions and in a liquid cooled bath. Simultaneous multiple realizations with capsule type SPRTs and long stem SPRTs have been done with subsequent evaluation of suitability of this type of fixed-point cell for routine calibrations and to determine the heat flux effect that influence the triple point plateau. The repeated realizations in liquid cooled bath with the capsule type SPRT has shown promising results in the terms of reproducibility that was 0.5 mK. The measured triple point cell value measured with this kind of calibrated sensor exhibited only minor divergence of 0.35 mK from the average of the published nominal temperature values 233.55565 K [5, 6, 7]. The long stem SPRT performed similarly in the terms of reproducibility with added heat flux effects. This research was made possible thanks to the project (18SIB02 - Realising the redefined kelvin) which has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme. This work is part of the opening activities for a future GSRN affiliated research facility.

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The different metrological performance between the two CO_2 triple point cells

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The prohibition of mercury from the action of Minamata Convention is the trigger to look for a substitution of mercury triple point. We consider that carbon dioxide is one of the most powerful candidates for the substitution race. We have reported the work we did on CO_2 triple point (Cell1) [1], and recently we designed another cell, whose working part is 25 cm long, 5 cm longer than Cell1's, and other parts of the two cells share the same size and structure.

We applied the same steps to the longer cell as we did on the first cell's realization. The temperature of the long working part cell at the CO_2 TP is 216.59125 (36) K at the melted fraction F=0.5 and 216.59131 (37) K at F=1.0, which is extracted from one single realization plateau. The temperature of Cell1 is 216.59130(36) K at F=0.5 and 216.59136 (37) K at F=1.0. The difference of temperature between the two cells is 0.05 mK at both F=0.5 and F=1.0, which is far less than 0.36 mK, the uncertainty of the temperature of the cells.

The span of the plateau is less than 0.08 mK, and the plateau is last more than 129 hours, the time span between F=0.3 and F=0.75 is 88 hours (less than Cell1, which is about 105 hours). From the time span of the plateau, we deduced that the block of upper solid CO_2 absorbed the main part of the heat leak.

From the melting plateau, we can deduce the purity of CO_2 in the longer cell is about 99.99985%, which is not as good as the first cell's 99.99989%.

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Evaluation of the triple point of xenon and temperature scales of SPRTs calibrated at the tripe point of xenon, carbon dioxide and sulfur hexafluoride

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From 13.8033 K to 273.16 K, the temperature standard is realized by using standard platinum resistance thermometer (SPRT) calibrated at fixed points of the international temperature scale of 1990 (ITS-90). The triple point of mercury (TPHg, 234.3156 K) is one of the important fixed points for the realization of the ITS-90. However, the use and transportation of mercury have been restricted because of its toxicity. To maintain the traceability of temperature measurement based on the ITS-90 under this restricted condition, the introduction of alternatives to substitute mercury is essential.

Previous studies suggested that the triple point of xenon (TPXe), the triple point of sulfur hexafluoride ($TPSF_6$) and the triple point of carbon dioxide ($TPCO_2$) have high possibility as candidates for alternatives [1-3]. In NMIJ/AIST, we developed apparatuses for the realization of the $TPSF_6$ and $TPCO_2$ and reported that the thermal treatment process before the realization of the triple point effectively reduced the width of the melting curve [3-4]. Recently, we have developed a similar apparatus for the TPXe, and realized the TPXe using xenon samples provided by several manufactures. Figure 1 shows the melting curves at the TPXe obtained from two xenon cells. The thermal treatment process also reduced the width of the melting curve at the TPXe as in the case of the $TPSF_6$ and $TPCO_2$. In this presentation, we will report the detail of this realization. In addition, we evaluated the temperature of temperature scales, T_{SF6}, T_{CO2} and T_{Xe}, obtained using SPRTs which were calibrated at the $TPSF_6$, $TPCO_2$ and TPXe, respectively, instead of the TPHg. Here, T_{XX} (XX is SF6, CO2 or Xe) is calculated by using interpolating function of the ITS-90. The temperature difference T_{XX}-T_{90} is within the uncertainty of T_{90} which is the temperature of the ITS-90, as shown in Fig. 2. We will report this in detail and the evaluation of the non-uniqueness and uncertainties of T_{XX} as well.

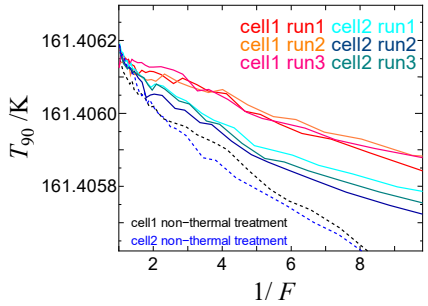

Fig. 1. Melting curves at the triple point of xenon.

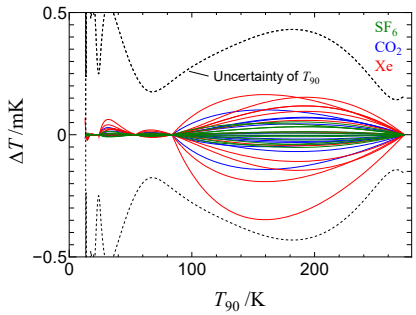

Fig. 2. The temperature difference T_{XX}-T_{90} (XX is SF6, CO2 or Xe) of SPRTs with four subranges.

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Parallel Session F2: High Temperature Fixed Points

Compilation and evaluation of binary metal-carbon phase transition temperatures
Donald R Burgess, Jr (National Institute of Standards and Technology, USA)

High-Temperature Fixed-Point Furnace Uncertainty
Dave Lowe and Graham Machin (National Physical Laboratory, United Kingdom (Great Britain)); Jose Manuel Mantilla and Maria-Jose Martin-Hernandez (Centro Español de Metrologia, Spain); Ferruccio Girard and Michael Florio (Istituto Nazionale di Ricerca Metrologica (INRIM), Italy); Mohamed Sadli and Frédéric Bourson (LNE-Cnam, France); Humbet Nasibli (TUBITAK-UME National Metrology Institute, Turkey); Özlem Pehlivan (TUBITAK UME, Turkey)

Furnace gradient and melt/freeze plateau manipulation using high-power laser beams
Eric W. M. van der Ham (National Measurement Institute Australia, Australia)

Compilation and evaluation of binary metal-carbon phase transition temperatures

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In this work, we have compiled and evaluated phase transition temperatures for metal-carbon and metal carbide-carbon compounds and selected recommended values for use on the temperature scale. There are 13 compounds with phase transition temperatures with low expanded uncertainties U=(0.15 to 0.4) K that could be used as secondary reference points. There are another ~30 compounds with high uncertainties that could not be used. A number of the systems have both MC-C(graphite) and M_aC_x-M_bC_y mixed-carbide phase transitions.

The highest fixed points on the ITS-90 temperature scale are the freezing points of silver (1234.93±0.08 K), gold (1337.33±0.10 K) and copper (1357.77±0.12 K) (all expanded uncertainties). There are a number of recommended secondary reference points for other metals above these temperatures: the freezing points of nickel (1728±2 K), palladium (1828.0±0.22 K), and platinum (2041.3±0.8 K).

There are six metal-carbon compounds (all first row transition metals, except Si-SiC) with phase transition temperatures with relatively low uncertainties that are candidates for secondary fixed points between the freezing point of copper and the melting point of palladium. These compounds, weight percent carbon, temperatures, and expanded uncertainties are: Fe-C[4.3%] (1426.76±0.23 K), Co-C[2.6%] (1597.48±0.14 K), Ni-C[2.1%] (1601.7±0.25 K), Mn_7C_3-C[8.6%][peritectic] (1603.9±0.4 K), Si-SiC[0.3%] (1679.9±0.2 K) and Pd–C[2.7%] (1764.94±0.26 K).

There are another eight phase transitions at higher temperatures (from Pt-C at 2011 K to ZrC-C at 3154 K). Higher temperature fixed points are necessary, because the inherent expanded uncertainty in radiometric measurements range about U=(0.6 to 1.8) K at (2000 to 3000) K. These transitions are: Pt–C[1.2%] (2011.66±0.26 K), Cr_7C_3-Cr_3C_2 [3.6%] (2015.26±0.88 K), Cr_3C_2-C[13.3%][peritectic] (2099.4±0.5 K), Ru–C[2.5%] (2226.93±0.37 K), Re-C[1.3%] (2747.5±0.18 K), WC-C[6.1%][peritectic] (3020.4±0.2 K),TiC_2-C[29.9%] (3033.8±0.1 K), and ZrC_2-C[21.8%] (3154.1±0.18 K). The Cr_3C_2-C peritectic point is an alternative to the eutectic points of the precious metal carbides Pd-C, Pt-C, and Ru-C.

There are ~30 metal carbides with phase transition temperatures at high temperatures that have large uncertainties ranging from Sc_3C_4 at 1995 K to HfC-C at 3446 K. The standard uncertainties are u=(4 to 50) K (median of ~20 K). With these high uncertainties, they are not candidates for secondary fixed points. These compounds, temperatures, and standard uncertainties (where reported) are the carbides of the main group elements: Be_2C-C (2012 K) and B_4C-C (2663±20 K); p-group elements: Al_4C_3-C[peritectic] (2425±15 K) and SiC-C[peritectic] (3103±40 K); first row transition metals: Sc_3C_4-C (1995 K) and VC-C (2750 K); second row transition metals: YC_2-C (2563 K), NbC_2-C (2601±17 K), MoC-C (2862±9 K), and ZrC-C (2920±50 K); third row transition metals: HfC-C (3446 K), TaC-C (3375 K), Os-C (3273 K), and Ir-C (2715 K).; lanthanides: EuC_2-C (2488 K), YbC_2-C (2488±40 K), LuC_2-C (2503±20 K), SmC_2-C (2513 K), TmC_2-C (2518±35 K), CeC_2-C (2519±4 K), PrC_2-C (2527±6 K), NdC_2-C (2533 K), DyC_2-C (2533±25 K), ErC_2-C (2533±25 K), HoC_2-C (2543±20 K), LaC_2-C (2544±15 K), TbC_2-C (2548±20 K), GdC_2-C (2553±30 K), and PmC_2-C (2554 K); and actinides: UC-UC_2 (2002±30 K), PuC_2-C (2523±20 K), UC_2-C (2723±30 K), and ThC_2-C (2773±35 K).

High-Temperature Fixed-Point Furnace Uncertainty

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High-temperature fixed-points (HTFPs, [1]) with specified values and uncertainties can be used to establish thermodynamic temperature values above the silver point. Current assigned temperatures had their uncertainties arbitrarily increased to make the assignment data consistent; with one or more participating institutes seemingly under-reporting uncertainty values. It was suggested, but not substantiated, that this was because variation in a furnace's thermal environment had not been fully accounted for [2]. As part of further HTFPs' temperature assignment to extend the available options for temperature dissemination[1] [3], the effect of changing temperature gradients on the realization of different HTFP blackbodies has been investigated. The temperature performance of HTFP blackbodies were assessed at different positions and with varying temperature gradients within furnaces. The position with smallest melting range, highest point of inflection and lowest difference between point-of-inflection (poi) and liquidus points was taken to be optimum (e.g, Fig.1). The effect on the poi and liquidus temperatures of different positions and deliberately induced gradients was assessed. The smallest difference was used as the best that could be achieved by careful positioning or setting of furnace set points. These values will be used as part of assigning thermodynamic temperatures to the HTFPs. The uncertainty components for the HTFPs investigated are reported in Table 1, and it is recommended they should be included in any uncertainty budget for HTFPs based on these alloys.

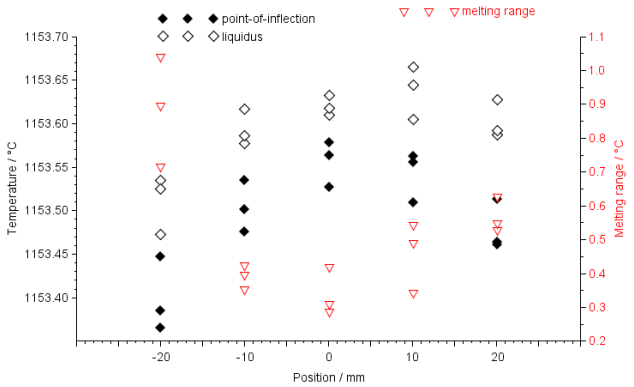

Fig. 1. Positional variation in melting range, point-of-inflection and liquidus for Fe-C in Chino furnace.

Table 1. Uncertainty (k=1) to be added to budget to account for non-uniform thermal environment; best, where the fixed-point position and furnace have been optimised and normal, where they have not.

Fixed Point	Best / mK	Normal / mK
Fe-C	25	30
Pd-C	50	120
Ru-C	30	150
WC-C	75	115

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Furnace gradient and melt/freeze plateau manipulation using high-power laser beams

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The high-power, monochromatic and coherent (collimated) properties of laser light can be employed in fixed-point thermometry to inject significant amounts of energy from a distance in either the furnace wall or fixed-point cell without disturbing the radiation thermometer in use. In this paper various techniques are demonstrated and discussed that find application in furnace and fixed-point diagnostics, spatial manipulation of melt/freeze interfaces, super-cool induction and compensation/elimination of furnace gradients.

At NMIA the reference LP5 pyrometer that is used for primary scale realization above the silver-point is permanently equipped with a 30 Watt CO_2-laser since 2017. The laser beam is mounted nearly collinear to the pyrometer optical axis and can be used to accurately and precise inject well-defined energy bursts during fixed-point operation. Prior to using this optical tool specific alignment and safe-use techniques were developed, next to verifying the invasive but not damaging nature of high-power densities on graphite.

Based on successful fixed-point cell and diagnostic use a new concept in laser-induced heating was further developed to manipulate furnace gradients as seen by fixed-point cells. A special graphite tubular sleeve insert was created that, once placed in the furnace, enables the use of five parallel laser beams to longitudinally deposit energy into furnace walls. First results of this concept are presented in this paper.

Parallel Session F3: Calibration Automation and Digitization

Digital Representation of Scales and Units for Temperature and Related Quantities
Peter Saunders (Measurement Standards Laboratory of New Zealand & Industrial Research Limited, New Zealand); Blair Hall (Measurement Standards Laboratory of New Zealand, New Zealand); Rod White (New Zealand)

A machine learning approach to automation and uncertainty evaluation for self-validating thermocouples
Samuel Charles Bilson, Andrew Thompson and Declan JL Tucker (National Physical Laboratory, United Kingdom (Great Britain)); Jonathan Pearce (NPL, United Kingdom (Great Britain))

Automated in situ calibrations in industrial applications
Marc Schalles (Ilmenau University of Technology, Germany); Pavo Vrdoljak (Endress Hauser, Germany)

Digital Representation of Scales and Units for Temperature and Related Quantities

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There is currently considerable interest in digitalization of measurement records and processes. One of the challenges for the measurement community is to find unambiguous digital representations of the wide variety of measurements associated with the use of the SI. The question of ambiguities is of particular relevance to those involved with the measurement of temperature and related quantities. For instance, the kelvin and degree Celsius are accepted units for both thermodynamic temperature and for temperature differences. Therefore, conversion of data expressed in kelvin to degrees Celsius or *vice versa* depends on the nature of the measured quantity, which cannot be determined by the units alone. Similarly, both absolute temperatures and temperature differences may be expressed using one of the two formal approximations to thermodynamic temperature provided in the *mise en pratique* for the definition of the kelvin [1], ITS-90 or PLTS-2000. For some applications, differences between the three scales are significant, and once again, the SI unit does not encode sufficient information to resolve the ambiguity.

A recent proposal for digital representation of measurement units and scales argues the case for an additional layer of metadata, the M-layer [2], expressly to enable resolution of such ambiguities. The traditional expression of a measured quantity is a couple: a numeric value paired with a unit name or symbol. An M-layer expression is a triplet, with the numeric value, an ‘aspect’, and a ‘scale’. The M-layer aspect is a generalization of the quantity kind tacitly associated with a unit. For example, temperatures reported using the thermodynamic, ITS-90, or PLTS-2000 scales each have different aspects.

The M-layer notion of scale combines a unit name, or other suitable reference, with the scale type (level of measurement). The scale types suggested by Stevens [3] classify the different forms of mathematical operations required to convert results from one scale to another. For instance, a temperature difference can be converted between kelvin and degrees Celsius by simple scaling, whereas conversion of absolute temperature data should also take account of the different zero points for each scale. When conversion involves only scale factors, such as the conversion of temperature differences, the type of scale for both scales is called a ‘ratio scale’, but when offsets are also involved, such as for absolute temperature conversions, at least one of the scales is of type ‘interval scale’.

By specifying the scale type as well as the unit, and combined with the aspect, the M-layer effectively removes ambiguity in digital representations of the SI.

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A machine learning approach to automation and uncertainty evaluation for self-validating thermocouples

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Thermocouples are in widespread use in industry, but they are particularly susceptible to calibration drift in harsh environments. Self-validating thermocouples, developed by NPL in collaboration with UK thermocouple manufacturer CCPI Europe, and being commercialized under the trade name INSEVA [1], aim to address this issue by using a miniature phase-change cell (fixed-point) in close proximity to the measurement junction (tip) of the thermocouple [2]. The fixed point is a crucible containing an ingot of metal with a known melting temperature. When the process temperature being monitored passes through the melting temperature of the ingot, the thermocouple output exhibits a 'plateau' during melting (see Fig. 1). Since the melting temperature of the ingot is known, the thermocouple can be recalibrated *in-situ*.

The main outstanding problem now is to automate the identification of the melting plateau. Quantifying the melting plateau to determine the onset of melting is reasonably well established, but requires manual intervention using techniques of zooming in on the region around the actual melting temperature, a process which can depend on the shape of the melting curve.

For the first time, we present a novel machine learning approach to recognise and identify the characteristic shape of the melting curve and, once identified, to quantity the point at which melting begins, along with its associated uncertainty (see Fig. 2). This removes the need for human intervention in locating and characterizing the melting point. Results from test data provided by CCPI Europe show 99 % accuracy of melting plateau detection. They also show a cross-validated R^2 of 0.99 on predictions of calibration drift.

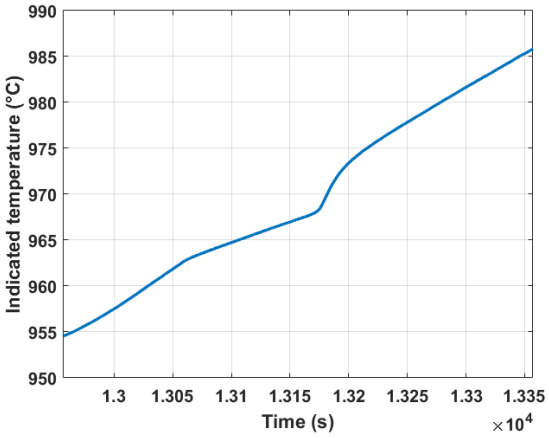

Fig. 1. Melting curve with plateau using a silver ingot.

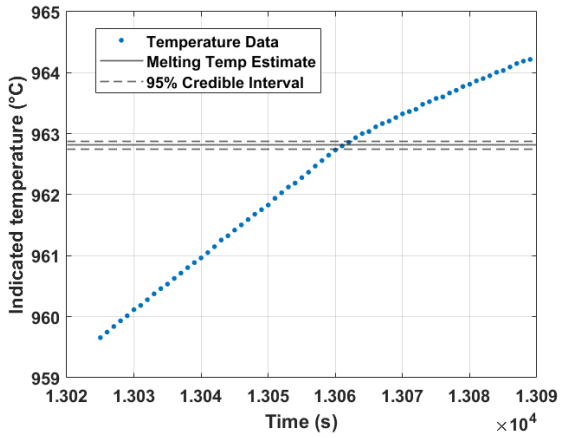

Fig. 2. Prediction and uncertainty estimates of the onset of melting.

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Automated in situ calibrations in industrial applications

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Small miniaturized fixed point cells can be used for in situ calibrations in laboratories [1] as well as in industrial applications [2]. As reference temperatures, the melting or freezing points are used. High attention must be paid, however, on the design and material of the crucible to retain the fixed point material. An alternative approach is to use phase transitions in reference materials in the solid state like ferroelectric materials. They provide an intrinsic polarisation, which is material specific in its physical characteristic. This polarisation vanishes when the Curie temperature of the individual material is exceeded and redevelops when the temperature drops below Curie temperature again. Since this is a reversible and reproducible procedure, one can use Curie temperature as a temperature reference point for calibrations. This idea was already presented at the conference ITS-9 [3]

Based on this principle, an industrial process thermometer was developed in the last decade, which facilitates an in situ calibration function. With it, the thermometer can be calibrated at its reference temperature (Curie temperature) directly in the process. It contains a standard resistance sensor and a ferroelectric reference sensor. Both sensors are placed in the thermometer tip and are read out in parallel (Fig.1). The resistance sensor and its electrical measurement circuit are recalibrated automatically when the process temperature triggers the phase transition at the Curie temperature. The calibration uncertainty of this dynamic calibration method in the process is 349 mK. It is estimated in an uncertainty calculation which takes many influencing quantities into account , like the reproducibility of the phase transition, dynamic influences, influences due to the process and many others.

The measurement principle will be explained in detail in the conference contribution. We will present tests of the thermometer, long term laboratory measurements of multiple thermometers with more than 3000 calibrations, field test calibration data recorded at industrial processes.

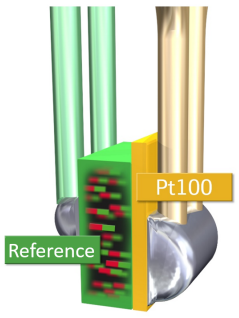

Fig. 1. Sketch .of sensor assembly

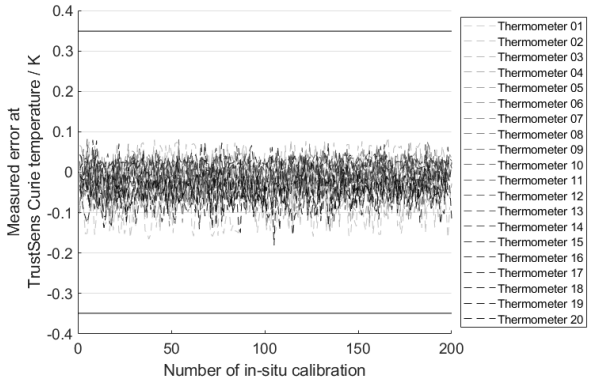

Fig. 2. Calibration data of 200 in situ calibrations of 20 thermometers

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Parallel Session F4: Photonic Methods for Trace Moisture and Humidity Measurements

Water measurement on the moon
Hisashi Abe (National Metrology Institute of Japan, Japan)
Invited

Improvement of the cavity in CRDS for high-precise measurement of trace moisture
Koji Hashiguchi (NMIJ, National Institute of Advanced Industrial Science and Technology (AIST), Japan)

Planar Polymer Waveguide Bragg Grating for Humidity Sensing
Stefaan Janssens, Sebastiampillai Raymond and Adam Swanson (Callaghan Innovation, New Zealand); Jeremy Lovell-Smith (Measurement Standards Laboratory of NZ (MSL), New Zealand)

Invited

Water measurement on the moon

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It has been more than half a century since the first humans landed on the moon in the Apollo 11 mission. Recently, the National Aeronautics and Space Administration (NASA) established a moon exploration program, called the Artemis program, to send humans to the moon again. International cooperation with other partner agencies, including Japan Aerospace Exploration Agency (JAXA), is also planned in this program. A long-term goal of this program is to build a base camp on the moon. In order to do this, one of the most important tasks that should be started first is to explore the lunar water, which is a potential resource for fuel (source of hydrogen and oxygen) and drinking water. In addition, the measurement of the isotopic ratios of water is of great interest, because it would provide valuable information on the origin of lunar water, which is deeply relevant to the history of the Earth-Moon system.

Recently, JAXA has formally started a Lunar Polar Exploration mission (LUPEX) to investigate the quantity and distribution of water. The mission plans to send instruments to the moon. National Metrology Institute of Japan (NMIJ) is working on the development of an instrument capable of measuring trace amount of water vapor as a collaborator in the mission. We selected cavity ring-down spectroscopy (CRDS) for the instrument. We were successful in the development of a prototype instrument based on CRDS [1, 2], which was small, lightweight, and robust. The performance of the instrument was evaluated using a primary trace-moisture standard previously also developed at NMIJ, which showed excellent results.

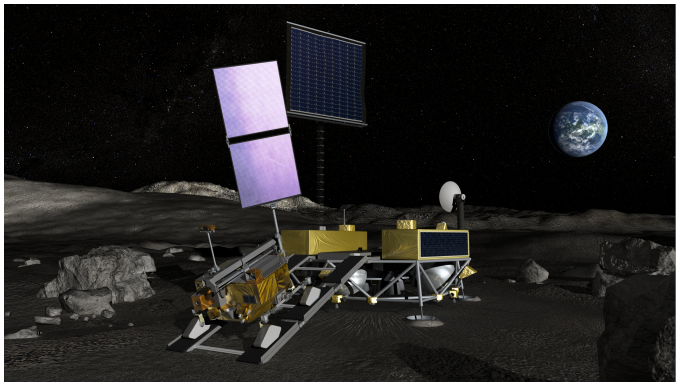

Fig. 1. LUPEX rover (©JAXA).

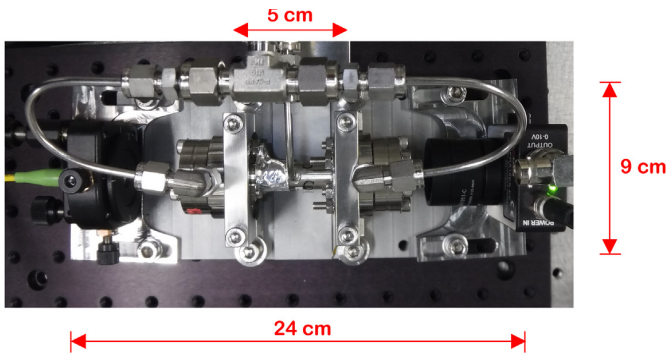

Fig. 2. Prototype of CRDS-based trace-moisture sensor [1].

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Improvement of the cavity in CRDS for high-precise measurement of trace moisture

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The high-precision measurement of trace water vapor (trace moisture) in gases is important in technology-intensive industries. We have developed measuring instruments for trace moisture using cavity ring-down spectroscopy (CRDS). In CRDS, an optical cavity consisting of highly reflective mirrors is used as a sample cell to extend the effective optical path length. It becomes more difficult to transmit a probe laser through the cavity if we use higher reflectivity mirrors. To solve this issue, we developed a simplified technique for laser control in CRDS, referred to as the "wavelength–meter–controlled" technique[1], and acquired the absorption spectra of H_2O near 7180 cm^{-1} at atmospheric pressure with good long-term stability[2].

In wavelength-meter-controlled CRDS, the length of the cavity is stabilized with reference to the frequency of a helium-neon (He-Ne) laser. This technique was developed by Hodges et al.[3]. To adjust the cavity length, a piezoelectric actuator was connected to a mirror mount at one end of the cavity. The piezo element has been placed outside the sample cell to avoid the effects of water desorption from the element.

To accurately measure trace moisture, the sample cell must be sealed using windows to prevent moisture from entering the cell from the outside. On the other hand, to be able to adjust the position of the mirror from the outside using the piezo element, it was necessary to install a window between the mirror and the piezo element. Because the window had to be close to the mirror, the reflected light from the window tended to cause fringe noise. In addition, fringe noise occurs when the reflections on both sides of the window become collinear.

In this study, to eliminate the fringe noise, we placed a window separate away from the mirror. In addition, the window was wedged so that the light reflections on both sides were not collinear. The mirror and the piezo element were directly connected and placed inside the cell. The gas flow is designed to reduce backflow to prevent desorbed moisture from the piezo element. Figure 1 shows the spectra obtained with the new cavity (red line) and with the previous cavity (black line with a slight offset). We could reduce the fringe noise. This improvement has made it possible to measure the trace moisture more precisely.

This study was supported in part by KAKENHI 21H01823, 22H02113 and by JST, CREST Grant Number JPMJCR2104, Japan.

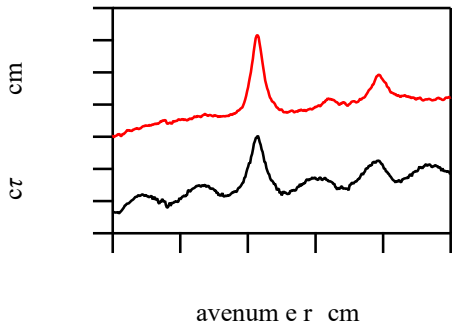

Fig. 1. Absorption spectra acquired using CRDS.

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Planar Polymer Waveguide Bragg Grating for Humidity Sensing

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Bragg grating based sensors are often used to measure temperature and relative humidity. Such optical sensors have several advantages over traditional electrical based sensors as they are immune from electromagnetic field interference, can be used for remote sensing in hostile environments, are easily multiplexed and have the potential to be manufactured at low cost [1]. Bragg gratings have been predominantly used in silica optical fibers, but these can also be inscribed in polymer optical fibers and planar waveguides. The Bragg wavelength of a planar waveguide grating is determined by the effective core refractive index and the grating pitch. For humidity sensing the response will depend on the change in refractive index and the expansion of the polymer due to absorption of water molecules [2]. Planar waveguide Bragg grating sensors were fabricated in thin polymer films and their humidity response characterized. Their properties were compared to commercially available polymer optical fiber grating sensors.

Waveguides were made in dye doped PMMA thin films by photolithography. Bragg gratings were inscribed in these waveguides using a phase mask and the spectrum of the Bragg reflection is shown in Fig.1a. The observed Bragg reflection shifts to longer wavelengths with an increase in relative humidity and the response of the grating is shown in Fig. 1b. The Bragg reflection shows a non-linear dependency on relative humidity with an average sensitivity of 50pm/%rh, which is similar to that found for polymer optical fiber gratings [1,2,3]. The measured time constant was found to be 4 min for increasing and 2 min for decreasing humidity. This is much faster compared to commercially available polymer optical fiber gratings which can be explained by the smaller thickness of the waveguides and hence shorter diffusion time [3]. A drift of the Bragg wavelength to shorter wavelengths was observed after cycling the humidity multiple times between 10%rh and 90%rh. This is likely caused by relaxation of strain present in the thin film due to the spin coating process used.

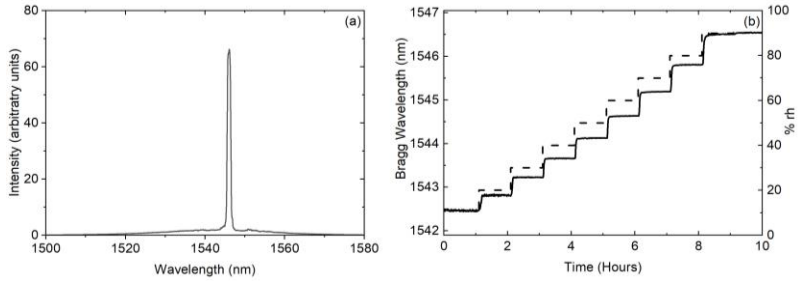

Figure 1 (a) Reflection spectra of the created grating. (b) Response of the grating (solid) to changes of relative humidity (dashed).

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Parallel Session G1: ITS-90 Fixed Points

Realization of the Melting Point of Gallium in a Stainless Steel-Cased Cell Using an Ethanol Heat Pipe
Xiaoke Yan (National Institute of Metrology (NIM), China); Ping Qiu and Jintao Zhang (National Institute of Metrology, China); Yuning Duan (National Institutue of Metrology (NIM), China); Steffen Rudtsch (Physikalisch-Technische Bundesanstalt, Germany)

Certification and Implementation of the Argon Triple Point in the Fluke SPRT Calibration Laboratory
Michael Coleman (Fluke Corporation, USA); Rong Ding (Fluke Electronics Corporation, USA)

Aluminum based eutectic fixed point cells in portable thermostat
Xiaofeng Lu (National Institute of Metrology, China & NIM, China); Jianping Sun and Tingting Zhang (National Institute of Metrology, China); Yikun Zhao (Xinjiang University, China)

25 years of ITS-90 traceability of the thermometry laboratory of Inmetro
Klaus Natorf Quelhas and Mario Anselmo Pereira Neto (Inmetro, Brazil); Bruno Mascarenhas Lozano (Instituto Nacional de Metrologia, Qualidade e Tecnologia - Inmetro, Brazil)

Realization of the Melting Point of Gallium in a Stainless Steel-Cased Cell Using an Ethanol Heat Pipe

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The melting point of gallium is an important defining fixed point of the International Temperature Scale of 1990 (ITS-90). Therefore, it plays an important role for realization and dissemination of the ITS-90 over the temperature ranges from -38.8344 ºC to 29.7646 ºC and 0 ºC to 29.7646 ºC. Moreover, due to its temperature near to room temperature, the Ga fixed point is widely used in oceanographic, clinical, biomedical and chemical laboratories.

Sealed gallium fixed-point cells with glass and Teflon composite containers have been developed and used at NIM for many years. In order to improve the robustness of Ga cells, many efforts have been devoted to developing a new stainless steel-cased gallium cell during recent years. Compared with an outer case made of glass, the stainless steel has a much higher mechanical robustness and a higher (about 12 times) thermal conductivity. Further improvements of the temperature uniformity around the Ga cell to obtain good melting plateaus were achieved by a copper-ethanol heat pipe accommodating the Ga cell. We present the procedure for developing the Ga cells and copper-ethanol heat pipe, the improved thermal characteristics, and its effects on the melting plateaus of gallium.

A serial of experiments has been carried out to characterize the performances of the new SS cased gallium cell. Due to the flattening ability of the heat pipe, the temperature uniformity within 13 cm from the bottom of thermometer well was no more than 1.3 mK. After using the copper-ethanol heat pipe as an isothermal liner, the temperature variations of the obtained plateau within 64 hours were in good agreement within 0.02 mK. Effects of the outer liquid-solid interface and double liquid-solid interfaces on the melting plateaus were investigated.

Finally, in order to confirm the equivalence of the new SS cased gallium cell, a bilateral comparison between NIM and PTB was performed at PTB in 2019. The comparison results show that the average temperature difference of the NIM cell (s/n: Ga-M-002) and the PTB cell (s/n: Ga648) amounts to 0.01 mK. This is attributed to the impurities within the fixed-point materials.

Certification and Implementation of the Argon Triple Point in the Fluke SPRT Calibration Laboratory

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This paper summarizes the project to certify and implement an argon triple point system into the Fluke SPRT calibration laboratory. For more than twenty years Fluke has provided ISO/IEC 17025 accredited SPRT calibration by fixed point over the range of -197 °C to 962 °C. Fixed point cells were used at all points except for -197 °C where a comparator device using the boiling point of liquid nitrogen and a NIST-calibrated capsule SPRT was used in place of the argon triple-point. To improve upon this setup the laboratory acquired an argon triple-point system, calibrated it, and implemented it into the SPRT calibration process. This paper gives the results of the project including heat flux (immersion) testing, well-to-well temperature uniformity testing, plateau repeatability testing, plateau stability testing, realization temperature verification, interlaboratory comparison results, and the certification uncertainty analysis. A description of the argon triple-point system is provided along with methods of dealing with non-ideal results that can occur when measuring temperature in the argon triple point system with metal sheath SPRTs.

Aluminum based eutectic fixed point cells in portable thermostat

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Between Aluminum and Zinc fixed points, there are no defined fixed points in two hundreds degree gap in the ITS-90. The eutectic alloy based on aluminium has the similar melting and freezing plateau as pure metal. Their temperature were just located between 419.527 ºC and 660.323 ºC [1,2]. To investigate the behaviour of the eutectic crucibles and reduce the cost, a special graphite cell was designed and filled with the proper ration of aluminium and silver, copper and zinc. They were all realized in a portable thermostat in turn, since the portable thermostat has the advantage of increasing temperature quickly and good uniformity in the bottom of the cavity. To avoid oxidation of graphite and metal, the cell was sealed in a welded stainless steel bottle. Graphite paper and block was used to reduce the contamination between the cells and stainless steel. A platinum resistance sputtering on the alumina was used to measure the temperature of the eutectic fixed points while it was calibrated up to 660 ºC based on the SPRT calibration method. The melting temperature was analysed based on the similar method of high temperature fixed point with the estimated uncertainty.

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25 years of ITS-90 traceability of the Thermometry Laboratory of Inmetro

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Since 1997, the Thermometry Laboratory (Later) of Inmetro has taken part in several comparisons of ITS-90 temperature standards to stablish the traceability of the SPRT calibrations. More recently, Inmetro took part in the key comparison CCT-K9 [1], which had its Draft B report approved last year, with very positive results. Along these 25 years, however, different standards were either purchased or developed, and some unfortunately failed and broke, so different fixed point cells were employed in some comparisons, which turns the task of keeping the traceability chain challenging.

In the late 1990's and earlier 2000's, technical limitations at Inmetro's Thermometry Laboratory allowed only performing SPRT calibrations using sealed ITS-90 fixed-point cells, resulting in bigger errors and uncertainties, naturally reflected in the results of the bilateral comparisons performed at the time. Starting in 2002, as new cells were purchased or manufactured at Inmetro, the old sealed cells gave place to new open fixed-point cells. In order to keep track of the traceability, the new cells were compared to the old ones and, when Inmetro took part of CCT-K9, the ITS-90 traceability chain was finally complete.

This work shows the result of a study that consolidated the results of all SPRT comparisons of that Later/Inmetro took part in since 1997, demonstrating that the traceability chain has been successfully maintained for more than two decades. By linking the results of all comparisons, we were able to determine the corrections and uncertainties of the fixed-point cells within the range between the triple point of argon (Ar, -189.3442 °C) and the freezing point of zinc (Zn, 419.527 °C, see Fig. 1), and to estimate what would have been Inmetro's results if the current reference standards were used in the previous comparisons - Fig. 2 illustrates for the estimated results for the Zn point.

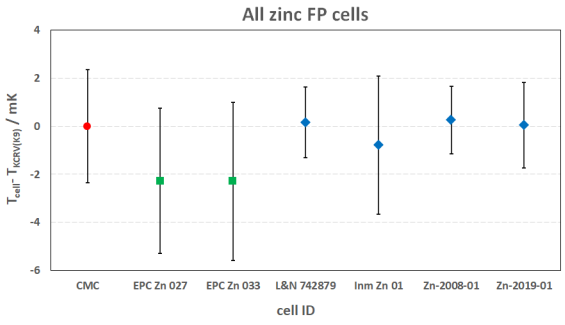

Fig. 1. Temperature differences and uncertainties for all Inmetro's Zn cells.

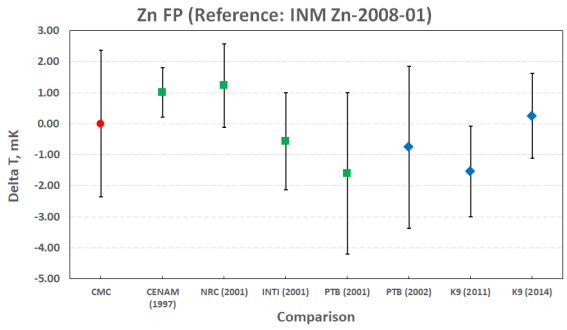

Fig. 2. Estimated comparison results if using Inmetro's reference Zn cell.

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Parallel Session G2: Thermal Imaging

Temperature spatial mapping using MEMS mirror steered radiation thermometry
Jon R Willmott (University of Sheffield, United Kingdom (Great Britain))

Imaging luminescence thermometry: Recent developments at NPL
Gavin Sutton and Aldo Mendieta (National Physical Laboratory, United Kingdom (Great Britain))

Thermographic Phosphor Digital Image Correlation: Overview and Current Progress
Caroline Winters, Elizabeth M.C. Jones, Linda E. Hansen, Kaitlynn M. Fitzgerald, Shannon E. Murray, Amanda R. Jones, Namir A. Huertas, Eric R. Westphal, Timothy J. Ruggles, William G. Gilliland and Luis J. Jauregui (Sandia National Laboratories, USA)

A Review and Advances in Thermal History Sensing for Turbine Applications
Joseph D Counte (University of Nottingham & Sensor Coating Systems Ltd., United Kingdom (Great Britain)); Jim Hickey, Silvia Araguas Rodriguez and Solon Karagiannopoulos (Sensor Coating Systems Ltd., United Kingdom (Great Britain)); Tanvir Hussain, Oriol Gavaldà Diaz and Halar Memon (University of Nottingham, United Kingdom (Great Britain)); Jörg P Feist (Sensor Coating Systems Ltd., United Kingdom (Great Britain))

Temperature spatial mapping using MEMS mirror steered radiation thermometry

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Traditionally, thermal imaging has been considered insufficiently accurate for the measurement of temperature in many industrial processes and scientific studies; therefore, single point thermometers have been used. Where a non-contact measurement is required, infrared radiation thermometers are required. We describe the development of a new "2-dimensional scanning" radiation thermometer. The thermometer is able to produce spatial maps of temperature (images) with measurement uncertainty for each pixel within 1 K, with a minimum measurable temperature of 750 °C and a spectral band of 0.85 to 1 µm. The instrument pixel field-of-view is 150:1 at 90% encircled energy. Particular challenges that were overcome included: minimising size-of-source effect within a complicated, multi-lens optical system; measuring infrared radiation with acceptable signal-to-noise ratio within a highly aperture limited (high f/#) system and maintaining a consistent measurement across all fields-of-view. Scanning of the radiation thermometer is by means of a microelectromechanical system (MEMS) mirror. We study the measurement uncertainty of the system as a spatially distributed matrix of radiation thermometer measurements and contrast the results with CMOS pixel array cameras that were, themselves, calibrated for temperature measurement. Three modes of measurement are considered: 1) Near-infrared; 2) wavelengths between 1 and 1.6 µm and 3) ratio thermometry. We demonstrate the utility of the new instrument by presenting results from trials undertaken within a steelmaking process.

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Imaging luminescence thermometry: Recent developments at NPL

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Accurate, traceable surface temperature measurements are critical in many high value manufacturing applications, particularly at elevated temperatures. Traditionally, surface temperatures are determined by infrared thermometry or sprung-loaded thermocouples. However, these approaches can have large uncertainties, due to unknown surface emissivity and background radiation in the former case and variable contact and heat-sink effects in the latter. Luminescence surface thermometry, where a coating applied to the surface is interrogated optically, has the potential to overcome these limitations and, when correctly applied, is independent of the surface emissivity and unperturbed by strong background thermal radiation. Here we describe two novel imaging luminescence thermometers developed at NPL, utilizing the ubiquitous thermographic phosphor Mg_4FGeO_6:Mn (MFG), one measuring the luminescence decay time and the other the spectral intensity ratio. For each instrument, the measurement principles, design, calibration, and measurement uncertainty are presented. Three applications of temperature measurement are then given: resistively heated strips for strain measurements [1], performance evaluation of photovoltaic cells [2], and metals processing with induction heating and comparison with thermal imaging [3]. Fig. 1. shows the spectral intensity ratio thermometer scheme used to measure inductively heated samples, with a comparison between the phosphor derived temperatures and those measured by embedded thermocouples.

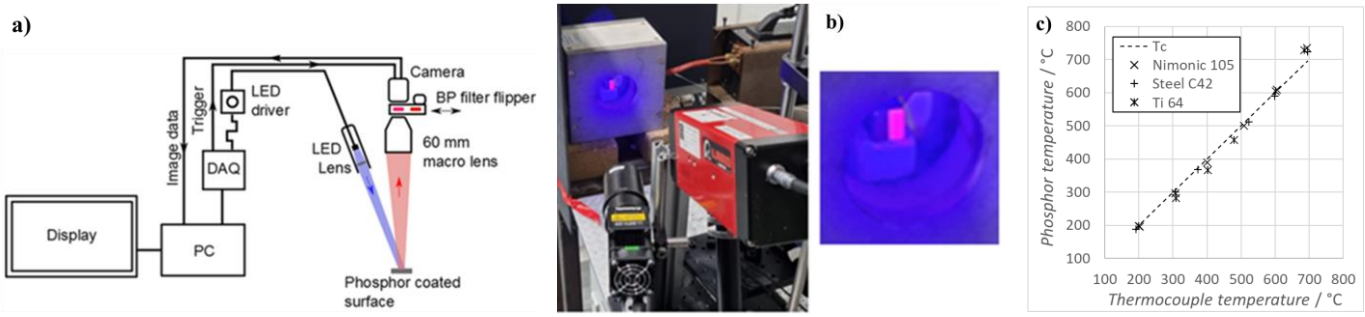

Fig. 1. Imaging intensity ratio phosphor thermometer: a) design scheme, b) measurements on an induction furnace, and c) phosphor temperature versus embedded thermocouple for three different engineering alloys.

The prospects for future development are discussed. These include extension of the current measurement temperature range (0 °C – 750 °C) to lower temperatures (-196 °C) for cryogenic and space sector applications, and higher temperatures (1200 °C+) for metals processing industries.

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Thermographic Phosphor Digital Image Correlation: Overview and Current Progress

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Thermographic phosphors have been combined with stereo digital image correlation, TP+DIC, to measure full-field surface strains and temperatures simultaneously. DIC was employed not only for strain measurements, but also for accurate image registration between the two cameras for two-color ratio thermography [1]. Manganese doped magnesium fluorogermanate (Mg3F2GeO4:Mn4+, MFG) deposited via aerosol deposition (AD) generated TP+DIC patterning to characterize the thermo-mechanical response of macro-scale 304L stainless steel dog bones during tensile testing at different strain rates [2]. The phosphor DIC pattern was then measured with two visible-light CMOS cameras (FLIR, Grasshopper 2.3 MP USB3.0), and a fiber-coupled spectrometer (Ocean Insight, HR2000+) for full-field and spatially averaged temperature measurements, respectively. TP+DIC successfully measured strains up to 0.8 mm/mm and temperatures up to 420 °K. However, tensile testing of the specimen relieved residual compressive stress from the AD process, causing an unexpected, discontinuous increase in emission brightness and an irreversible 5-10 K bias error. This work explores that phenomenon in detail.

AD has been developed to produce robust, dense coatings of thermographic phosphors; these binderless coatings maintain the thermal sensitivity of neat phosphor powder [3]. Scanning Electron Microscope images of in-situ tensile loaded AD coatings showed accommodation of the substrate strain through cracking and debonding. This revealed the need for a flexible, stretchable phosphor coating for deforming metal specimens. Meso-scale stainless steel dog bones were coated with a polymer-based phosphor ink in a DIC speckle pattern. When tensile loading was applied under a microscope, the ink remained well bonded. DIC calculations inferred that the strain on the ink coating matched the strain on the substrate within 4% error at 0.05 mm/mm applied substrate strain, while the strain on the AD coating remained near 0 mm/mm and the coating partially debonded. Spectrally resolved emission from the phosphor was measured, and the ratio method was used to infer temperature with an uncertainty of 3 °K.

This presentation will introduce TP+DIC, best practices in generating DIC patterns to deform conformally with test articles, and current applications for this multi-modal diagnostic. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government. This work was supported by the Laboratory Directed Research and Development program SNL is managed and operated by NTESS under DOE NNSA contract DE-NA000352.

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A Review and Advances in Thermal History Sensing for Turbine Applications

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The key objective for development engineers remains the increase in engine efficiency and making the best use of available fuel. This will see the continued introduction of new combustion technologies, high temperature materials and air-cooling methodologies to support higher more efficient firing temperatures. Accurate temperature mapping systems are a must-have necessity to achieve quick component validation and early market entry.

In the first part of this paper, traditional technologies such as thermochromic paints, thermal crystals and templugs are compared to an emerging technology based on luminescent thermal history paint and coatings. Significant properties of these technologies such as durability, calibration, spatial resolution, temperature resolution, accuracy and cost effectiveness are assessed. A comparison matrix of the techniques is presented to act as a user guide for practitioners in the turbine industry.

In the second part of this paper, recent advances in luminescent thermal sensing technology are examined. These temperature sensing methods utilise spectral and temporal material characteristics to determine temperature. The material design and manufacture of these coatings and paints are discussed and reviewed with a view on applications in modern engine designs. A comprehensive summary is provided with recent industrial applications of this technology detailed.

Thermal History Coatings (THCs) are temperature memory materials comprising luminescent ceramic coatings which respond to sintering to record the previous maximum exposure temperature. This temperature data can be sampled at thousands of points across a coated engine component to map thermal patterns in high resolution.[1] THCs can also withstand high temperatures for extended periods to deliver temperature maps.[2]

In the concluding part of this paper, advanced concepts for future applications of THCs are outlined. A specific example is detailed in a new study that showcases the viability of THCs for sub surface measurements. A THC is covered by a nickel flash coating to protect the sensing layer during operation. Post flash coat removal, the THC results show a visible temperature gradient consistent across 2 components. The results indicate the feasibility of this technique to measure sub surface temperatures previously unobtainable.

This paper reviews the available temperature measurement toolbox available to OEM component designers including a novel thermal history technology with advanced applications.

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Parallel Session G3: New Technologies for Harsh and High Temperature Process Measurements

Practical, driftless, traceable thermometry at the point of measurement
Jonathan Pearce (NPL, United Kingdom (Great Britain)); Declan JL Tucker, Radka Veltcheva and Graham Machin (National Physical Laboratory, United Kingdom (Great Britain))
Invited

The Challenges And Some Solutions In The Development Of A Johnson Noise Thermometer
Paul Bramley and David G M Cruickshank (Metrosol Limited, United Kingdom (Great Britain))

Calibrated Sapphire Fiber Bragg Grating Thermometer for High-Temperature Process Monitoring
Stephan Krenek and René Eisermann (Physikalisch-Technische Bundesanstalt (PTB), Germany); Tobias Habisreuther (Leibniz Institute of Photonic Technology (IPHT), Germany); Sigurd Simonsen (Elkem ASA Technology, Norway)

Invited

Practical, driftless, traceable thermometry at the point of measurement

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Accurate, traceable thermometry for process control and monitoring is synonymous with energy efficiency, reduced greenhouse gas and toxic gas emissions, product yield, and safety. Harsh environments (e.g. high temperature, ionizing radiation, space) place severe demands on ongoing traceable temperature measurements. Here some developments in contact thermometry are described, aimed at overcoming specific practical measurement challenges[1].

In demanding process monitoring applications, as the sensor materials degrade in-process, the sensor drifts out of calibration. We describe three ways to mitigate this, the first with a practical primary Johnson noise thermometer, and the second and third with self-validating techniques based on miniature fixed-point cells:

- The technology readiness level of practical Johnson noise thermometry (JNT) has been elevated substantially by Metrosol Limited, with support from NPL, to bring it closer to practical application and commercialization [1]. JNT has the potential to provide truly driftless thermometry for harsh environments (e.g. nuclear decommissioning and waste storage). This represents the first practical implementation of the redefined kelvin in line with the 'Mise en pratique for the definition of the kelvin in the SI' [2] issued by the BIPM Consultative Committee for Thermometry (CCT) and supported by the CCT strategy (2021-2030+).
- A recent demonstration of the long-term robustness and utility of a slim integrated self-validating thermocouple (INSEVA), which is a collaboration between NPL and CCPI Europe [3,4], in industrial heat treatment applications is outlined. Externally the device looks the same as a regular process control thermocouple, facilitating integration in process facilities. Devices using the melting points of silver (961.78 °C), gold (1064.18 °C), copper (1084.62 °C) and iron-carbon (1153 °C) were used. A requirement for industrial uptake is automation of the recognition and characterization of the melting curves, which is resistant to conventional algorithms. A new method based on supervised machine learning is summarized.
- Miniature phase-change cells for *in-situ* traceable calibrations in a space-borne calibration blackbody are of interest in earth observation applications due to the effects of extreme vibration (on launch), temperature variations and cosmic radiation on the platinum resistance thermometers used in instrumentation on board spacecraft [5]. The latest developments at NPL towards providing *in-situ* in-orbit sensor calibration, in collaboration with RAL Space, are described. The traceably calibrated 'phase-change cells' operate in the temperature range from 0 °C to 30 °C providing calibration at the melting points of water (0 °C), gallium-indium alloy (15.7 °C) and gallium (29.7646 °C) with expanded uncertainties of between 10 mK and 30 mK.

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The Challenges And Some Solutions In The Development Of A Johnson Noise Thermometer

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Johnson noise thermometers are of interest in two main applications. Firstly, with the redefinition of the Kelvin in 2019 [1] there is a need for a practical primary thermometer that makes use of the newly fixed Boltzmann constant to realise the Kelvin. Secondly, a Johnson noise thermometer measures all the properties required to determine true thermodynamic temperature and as such is immune to the problem of calibration drift which all current practical thermometers experience and which is a particular problem in harsh environments.
We have developed a new technique for the realisation of a practical Johnson noise thermometer that overcomes the problems with prior art realisations and offers adequate uncertainty within a response time (0.1% in 6s) that is acceptable for metrology and industrial applications [2],[3]. In trying to realise a practical implementation of this technique, we have encountered a number of technical problems. These include the difficulty in generating a calibration signal with low uncertainty (<0.01%) over the working bandwidth 10kHz-1MHz, traceability to national electrical standards, producing an amplifier with low enough noise, minimising aberrations that contaminate the calibration signal, the effect of leakage in the probe insulation, processing the high data rate in real time and electromagnetic interference. In this paper we discuss the problems we have encountered in the development of a practical Johnson noise thermometer and some of the solutions.

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Calibrated Sapphire Fiber Bragg Grating Thermometer for High-Temperature Process Monitoring

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Accurate and reliable temperature measurement in high-temperature industrial environments is crucial for process optimization and monitoring of production facilities. This helps to reduce energy consumption and increase safety. Two of the biggest challenges for conventional electrical sensors, such as thermocouples, are rapid temperature changes and strong electromagnetic fields, such as those generated by high-voltage components or inductive furnaces. The result is accelerated aging and signal distortion, respectively. Sapphire-based optical fibers are well suited for these demanding applications due to their electromagnetic immunity and largely chemical inert nature. It has been shown that fiber Bragg gratings inscribed in monocrystalline multimode sapphire fibers (S-FBGs) are suitable for operation up to 1900 °C [1].

In previous work we demonstrated a hybrid sensor concept using S-FBG with an additional thermocouple [2]. S-FBG and thermocouple were calibrated traceable to the International System of Units at temperature fixed points, including the associated uncertainty budgets (thermocouple: $U_{k=2} \approx 1$ K ... 4 K; S-FBG: $U_{k=2} \approx 10$ K ... 14 K). Subsequently, the sensor was used for process monitoring in a 3-week field trial at an industrial silicon purification process with temperature cycles up to 1600 °C. During this time, the readings from both sensor elements agreed well within their combined uncertainty. A follow-up measurement of the sensor after this field trial and transport of the measurement system and sensor showed a change of less than 0.5 K at the Cu fixed point (1084.62 °C). To achieve this measurement repeatability and uncertainty, a signal processing of the reflected S-FBG spectrum was developed that uses an analytical expression for the long wavelength edge of the peak. This method of determining the wavelength position at a given temperature showed an order of magnitude better stability against peak shape changes due to aging compared to a standard peak-fitting methods.

Unavoidable mode variations caused by mechanical mode mixing are the main remaining source of measurement uncertainty. A systematic investigation was performed using an automated mechanical mode mixer. Using this approach an uncertainty of less than 2 K was achieved for the comparative measurements at the Cu fixed point. In the future, this will allow uncertainties comparable to thermocouples. We present and discuss the limitations of this method in terms of the achievable measurement accuracy as a function of the acquisition time.

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Parallel Session G4: Low Temperature Thermometry

Direct comparison of 3He and 4He vapor-pressure thermometers at LNE-Cnam within their overlapping temperature range
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A comparison of Germanium and Cernox® Cryogenic Temperature Sensors Over the 1 K to 27 K Temperature Range
Scott Courts (Lake Shore Cryotronics, Inc. & Otterbein University, USA); Brian Courts (Lake Shore Cryotronics. Inc., USA)

Establishing and Maintaining the ITS-90 Wire Scale at CAS using Rhodium-Iron Resistance Thermometers from 5K to 24.5K
Haiyang Zhang (The Technical Institute of Physics and Chemistry of the Chinese Academy of Sciences, China); Yao-Nan Song, Xiang-Jie Kong and Bo Gao (Technical Institute of Physics and Chemistry of the Chinese Academy of Sciences, China); Fernando Sparasci (Laboratoire Commun de Métrologie LNE-Cnam, France); Laurent Pitre (LNE-Cnam, France); Ercang Luo (Technical Institute of Physics and Chemistry of the Chinese Academy of Sciences, China)

Direct comparison of ^{3}He and ^{4}He vapor-pressure thermometers at LNE-Cnam within their overlapping temperature range

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The International Temperature Scale of 1990 defines the temperature in the range between 0.65 K and 5.0 K in terms of the vapor pressure of the two isotopes of helium, ^{3}He and ^{4}He. The ^{3}He isotope is used between 0.65 K and 3.2 K, and the ^{4}He isotope is employed in the range from 1.25 K to 5.0 K.

LNE-Cnam has developed an apparatus for vapor pressure thermometry with two separate gas systems installed in the same cryostat. One is dedicated to ^{3}He and the other to ^{4}He. Each one is equipped with its own vapor-pressure chamber, to avoid any mixing and preserve the purity of the two gases. The two chambers are within the same copper block to ensure their temperature equality. The apparatus is cooled by a commercial dilution refrigerator [1]. The setup allows the simultaneous realization of the two temperature definitions, and therefore a direct comparison, without any transfer standard.

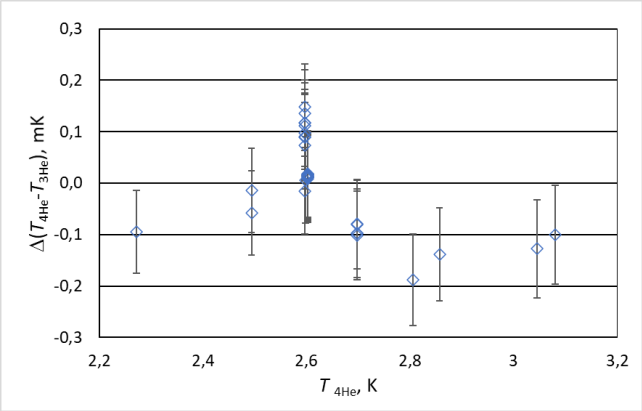

Fig. 1. Results of the comparison between the ^{3}He and ^{4}He vapor pressure thermometers.

A comparison of the two temperature definitions was carried out between 2.2 K and 3.2 K. The differences did not exceed 0.2 mK (fig 1), and the agreement with a previous study by Meyer and Reilly [2] was within 0.5 mK. This work presents the results of the comparison and an estimated uncertainty budget.

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A comparison of Germanium and Cernox® Cryogenic Temperature Sensors Over the 1 K to 27 K Temperature Range

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The ability of a national standards laboratory to disseminate a temperature scale relies entirely on the stability of the available secondary temperature standards. For many years, germanium resistance thermometers (GRTs) were the accepted secondary thermometer of choice below 27.5 K. Rhodium-iron resistance thermometers (RIRTs) have supplanted their use in many standards laboratories, but GRTs are still preferred in some applications due to their smaller size and high sensitivity. Following a trend over the past few decades, high quality thermometer standards for the cryogenic temperature range, including GRTs and RIRTs, have become harder to both produce and procure. Lake Shore Cryotronics, Inc. (LSCI) has produced GRTs for 50 years and used them both to maintain traceability to the National Institute of Standards and Technology (formerly The National Bureau of Standards) and as working standards in their temperature calibration facility. Currently, outside of national standards laboratories work, the 1 K to 27 K temperature is most often served by Cernox® resistance thermometers (CxRTs), model CX-1050-SD or CX-1050-AA, also produced by LSCI. Over the past thirty years, research performed at Lake Shore has examined the stability of CxRTs with regard to room-temperature storage time, thermal cycling, and mechanical shock.

This work provides a comparison of germanium and Cernox resistance thermometers' properties and performance over the 1 K to 27 K temperature range with regard to temperature resolution, short-term and long-term stability, stability over extended thermal cycling, and robustness. Over the 1 K to 27 K temperature range, GRTs and CxRTs provide similar resolution for the same instrumentation. In short term stability test at 4.2 K, these data show that GRTs are stable to the ±0.5 mK while CxRTs are stable to the ±1 mK level. Over extended periods of repeated thermal cycling to room temperature, GRTs remain stable to about ±2 mK below 10 K and ±5 mK above 10 K. While the average stability of a test group of CxRTs is on par with the GRT stability, the individual device stability has greater variability. With regard to robustness in handling, in drop tests the CxRTs remained more stable than the GRTs.

Establishing and Maintaining the ITS-90 Wire Scale at CAS using Rhodium-Iron Resistance Thermometers from 5K to 24.5K

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The International Temperature Scale ITS-90 is a set of guidelines for temperature measurement. It provides a method to ensure accurate and consistent results. The procedures outlined in ITS-90 are used to calibrate specified practical thermometers, such as platinum resistance thermometers, using defined fixed points. The goal of ITS-90 is to approximate thermodynamic values as closely as possible while maintaining precise and reproducible temperature values. However, direct realizations of the ITS-90 below 24.5K require relatively sophisticated apparatus and time-consuming experiments, and consequently no laboratory in the world have realize all since more than 28 years. In practice, it is acceptable to use calibrated rhodium-iron resistance thermometers (RIRTs) to accurately maintained, disseminated the ITS-90 as in Ref. [1]. To better reproduce ITS-90 between 5K and 24.5K, three RIRTs, two of which calibrated by National Physical Laboratory (NPL) and one by National Institute of Standards and Technology (NIST), were employed in the present work. First, a local ITS-90 temperature $T_{90,CAS}$ was established based on the weighted mean values of T_X read by the three calibrated RIRTs with X=NPL1, NPL3 and NIST. Then the mathematical relationships between $D(T_X) \equiv T_{90,CAS} - T_X$ and T_X were determined for each thermometer and used to study the long-term stability and the reproducibility of $T_{90,CAS}$ during the past 4 years. The results show that the stability and reproducibility of $T_{90,CAS}$ are respectively better than ±0.028mK and ±0.058mK in 4 years, shown in Fig.1. The present $T_{90,CAS}$ has been used as a baseline in the measurement of thermodynamic temperature by single pressure refractive-index gas thermometry (SPRIGT) [2], and will be continue to play a key role in thermometer calibration and international comparison of no matter ITS-90 or thermodynamic temperature in future.

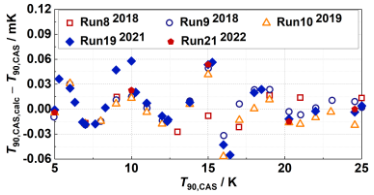

Fig. 1. The comparison results between $T_{90,CAS,calc}$, reproduced by the NIST calibrated RIRT from $D(T_{NIST})$ equation, and the weight mean value $T_{90,CAS}$, experimentally determined the three RIRTs, in different runs of SPRIGT during 4 year.

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Poster Session 1: Calibration Methods, Comparisons, SPRTs, Thermistors, Fixed Points, and Thermodynamic Temperature

Study on Immersion Effects and Self-heating in Various Heat Sources
Frank Liebmann (Fluke Corporation, USA)

Measuring the Performance of Temperature and Humidity Chambers in accordance with IEC60068-3-6:2018
Julian Cheung, Brenda Lam, Stanley Ma and Amber Wan (Standards and Calibration Laboratory, Hong Kong)

A Novel Surface Calibrator using Heat Pipe for Surface Probe Calibration
Yan Fan and Li Wang (National Metrology Centre, ASTAR, Singapore)

On the accuracy of surface temperature measurements with pipe clamp probes
Marc Schalles (Ilmenau University of Technology, Germany)

Type 3 Non-Uniqueness in Standard Platinum Resistance Thermometers in the Temperature Range from 83 K to 353 K
Radka Veltcheva (National Physical Laboratory, United Kingdom (Great Britain)); Carmen Garcia Izquierdo (2Centro Español de Metrología, Spain); Richard Rusby (National Physical Laboratory, United Kingdom (Great Britain)); Jonathan Pearce (NPL, United Kingdom (Great Britain)); Elena Gomez (CEM, Spain); Aleksandra Kowal (Instytut Niskich Temperatur i Badan Strukturalnych, Poland)

Least squares approach to standard platinum resistance thermometer subrange inconsistency reduction with redundant gallium and indium fixed points
Vincencij Žužek (University of Ljubljana, Slovenia); Jonathan Pearce (NPL, United Kingdom (Great Britain)); Richard Rusby (National Physical Laboratory, United Kingdom (Great Britain)); Andrea Peruzzi (National Research Council, Canada); Jovan Bojkovski (MIRS/UL-FE/LMK, Slovenia)

SPRT stability as a limiting factor in the precision of interlaboratory comparisons
Tobias Herman (NIST, USA); Michal Chojnacky (National Institute of Standards and Technology, USA)

A Bilateral comparison between CEM and INM on the calibration of SPRTs in fixed points in the range from 234.315 6 K to 933.473 K
Dolores Del Campo and Elena Gomez (CEM, Spain); Ciro Alberto Sánchez (Instituto Nacional de Metrología, Colombia); Edgar Mendez-Lango (Centro Nacional de Metrologia, CENAM, Mexico); Andrés

Jhovanny Bohorquez Garzon and Sergio Andres Carvajal (Instituto Nacional de Metrología, Colombia)

Measurement of light-piping effect at the freezing point of silver using a high temperature standard platinum resistance thermometer (HTSPRT)
Vincencij Žužek (University of Ljubljana, Slovenia); Semir Čohodarević and Nedžadeta Mutapčić (Institute of Metrology of Bosnia and Herzegovina, Bosnia and Herzegovina); Jovan Bojkovski (MIRS/UL-FE/LMK, Slovenia)

The stability of chip-size thermistors for miniature atomic clocks
Ikuhiko Saito, Hideki Ogura and Shinya Yanagimachi (National Institute of Advanced Industrial Science and Technology, Japan)

A New Heat Pipe Standard Resistor Thermostat
Xiaoke Yan (National Institute of Metrology (NIM), China); Wei Wang (Henan Agricultural University, China); Yuning Duan (National Institutue of Metrology (NIM), China); Jintao Zhang (National Institute of Metrology, China)

From CCT-K7 to CCT-K7.2021: approaching the definition of the triple point of water temperature
Sergey Dedyulin (National Research Council of Canada, Canada); Andrea Peruzzi (National Research Council, Canada); Dolores Del Campo (CEM, Spain); Carmen Garcia Izquierdo (2Centro Español de Metrología, Spain); Elena Gomez (CEM, Spain); Klaus Natorf Quelhas and Mario Anselmo Pereira Neto (Inmetro, Brazil); Bruno Mascarenhas Lozano (Instituto Nacional de Metrologia, Qualidade e Tecnologia - Inmetro, Brazil); Liliana Eusebio (IPQ, Portugal); Inseok Yang (Korea Research Institute of Standards and Science, Korea (South)); Fernando Sparasci (Laboratoire Commun de Métrologie LNE-Cnam, France); Catherine Martin (LNE-Cnam, France); Lara Risegari (Laboratoire Commun de Métrologie LNE-Cnam, France); Peter Saunders (Measurement Standards Laboratory of New Zealand & Industrial Research Limited, New Zealand); Ellie Molloy (Measurement Standards Laboratory of New Zeland, New Zealand); Xiaoke Yan (National Institute of Metrology (NIM), China); Jianping Sun, XiaoJuan Feng and Jintao Zhang (National Institute of Metrology, China); Mong-Kim Ho (National Measurement Institute, Australia); Tohru Nakano (AIST, Japan); Januarius Vincentius Widiatmo and Ikuhiko Saito (National Institute of Advanced Industrial Science and Technology, Japan); Efrem Ejigu (National Metrology Institute of South Africa, South Africa); Richard Rusby (National Physical Laboratory, United Kingdom (Great Britain)); Jonathan Pearce (NPL, United Kingdom (Great Britain)); Steffen Rudtsch and Lars Buenger (Physikalisch-Technische Bundesanstalt, Germany); Murat Kalemci (TUBITAK UME, Turkey);

Ali Uytun (TUBITAK-UME National Metrology Institute, Turkey); Conny Bruin-Barendregt and Jatthijs Panman (VSL, The Netherlands); Rod White (New Zealand); Antonio Possolo (National Institute of Standards and Technology, USA)

The CCT Task Group on Digitalization
Patrick M.C. Rourke (National Research Council Canada, Canada); Christof Gaiser (PTB, Germany); Roberto Gavioso (INRiM, Italy); Yasuki Kawamura (National Institute of Advanced Industrial Science and Technology (NMIJ, AIST), Japan); Graham Machin (National Physical Laboratory, United Kingdom (Great Britain)); Ingmar Mueller (Physikalisch-Technische Bundesanstalt (PTB), Germany); Mohamed Sadli (LNE-Cnam, France); Peter Saunders (Measurement Standards Laboratory of New Zealand & Industrial Research Limited, New Zealand); Inseok Yang (Korea Research Institute of Standards and Science, Korea (South)); Jintao Zhang (National Institute of Metrology, China)

Forty years of sealed samples of CO2 for the measurement of its triple point as a possible replacement for the triple point of mercury
Franco Pavese (Torino, Italy)

Develop a new optimized procedure for the updated argon triple point system
Javier García Skabar (INTI - Instituto Nacional de Tecnologia Industrial, Argentina); Mariano Gonzalo Liste and Rocío del Pilar Napan Maldonado (INTI, Argentina); Brenda Tenaglia Giunta (UNSAM, Argentina)

A Closed-Cycle Immersion Cell Platform for Noble Triple Points
Christopher Alvarez (Goddard Space Flight Center, USA); Jay Nanninga (NIST, USA); Weston L Tew, Jr (National Institute of Standards and Technology, USA)

Construction and evaluation of gallium point cells
Ikuhiko Saito, Januarius Vincentius Widiatmo and Hideki Ogura (National Institute of Advanced Industrial Science and Technology, Japan)

Manufacture and evaluation of a new zinc reference standard cell of Inmetro
Bruno Mascarenhas Lozano (Instituto Nacional de Metrologia, Qualidade e Tecnologia - Inmetro, Brazil); Klaus Natorf Quelhas (Inmetro, Brazil); Luiz Tarelho (Instituto Nacional de Metrologia, Qualidade e Tecnologia, Brazil); Ricardo Savio Teixeira Moretz Sohn (National Institute of Metrology Quality and Technology - Inmetro, Brazil)

Acoustic gas thermometry and thermodynamic temperature measurement at KRISS
Inseok Yang (Korea Research Institute of Standards and Science, Korea (South))

T-T90 Measurements using Acoustic Gas Thermometer up to Gallium Point in Neon Gas
Januarius Vincentius Widiatmo, Tetsuro Misawa and Ikuhiko Saito (National Institute of Advanced Industrial Science and Technology, Japan); Tohru Nakano (AIST, Japan); Yasuki Kawamura (National Institute of Advanced Industrial Science and Technology (NMIJ, AIST), Japan)

Measurements of the Acoustic Virial Coefficients of Argon from 118 K to 323 K
Robin Underwood (NPL, United Kingdom (Great Britain))

Study on Immersion Effects and Self-heating in Various Heat Sources

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In contact thermometry calibration of resistive probes, there are a number of factors which cause measurement uncertainty. Among these are measurement noise and repeatability, uncertainty due to the measurement readout, true temperature of the heat source, immersion effects, and self-heating.

Both immersion effects (sometimes referred to as stem effect) and self-heating can be influenced by a number of factors. The obvious factors include thermal conduction of the probe's stem, immersion depth of the probe into the heat source medium, excitation current, and probe resistance. These factors are all directly related to the probe itself. There are other factors related to heat transfer between the probe and the heat source medium that effect both immersion effects and self-heating. These are mainly due to the convective or conductive heat transfer between the probe and the heat source. These will change with temperature, the heat source medium used, and if a stirred liquid medium is used, it will also change based on the stirring velocity of the bath fluid.

This paper covers a few basic concepts and terms related to a resistive temperature probe calibration. It speaks to the basics of heat transfer in a temperature probe calibration. It then discusses the results of an immersion effect and self-heating study. The study is based on data in different heat sources including stirred liquid baths, a fixed-point, and a dry-block calibrator. The paper discusses the results and speaks to how results of such tests may be interpreted by the user.

Measuring the Performance of Temperature and Humidity Chambers in accordance with IEC60068-3-6:2018

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Temperature and humidity chambers are widely used for testing of biological items, industrial products, materials, electronic devices and components, etc. and calibration of temperature and humidity sensors, thermohygrometers and other humidity devices. It is important to verify the performance of a temperature and humidity chamber regularly to ensure that its environment is in conformity with target specifications.

At the Standards and Calibration Laboratory (SCL), a method was developed with reference to IEC 60068-3-5:2018 [1] to measure the performance of a temperature chamber. Confirmation of the Performance of Temperature Chambers had been discussed in a previous publication [2]. A multi-channel temperature logger with platinum resistance thermometer sensors was used for temperature measurement.

The method for temperature measurement described in [1] and the method for humidity measurement, which was developed with reference to IEC 60068-3-6:2018 [3] using a dew-point hygrometer as humidity measuring sensor, were used to verify the performance of a temperature and humidity chamber. In this paper, the equipment setup and detailed procedure for measurement of the achieved humidity, humidity fluctuation (in time domain), humidity gradient and humidity variation in space (both in spatial domain) of a chamber are provided. Examples of measurement results together with the uncertainty evaluation are presented.

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A Novel Surface Calibrator using Heat Pipe for Surface Probe Calibration

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In this paper, a unique surface calibrator using heat pipe technology was proposed to enhance the accuracy of the surface probe calibration in National Metrology Centre (NMC), A*STAR. Cesium heat pipe, which was supplied by National Institute of Metrology of China (NIM China), was applied in the surface probe calibration first time in Singapore. The dedicated calibration system including the furnace design, heating system and control system was designed, constructed, and developed by NMC to support the calibration service of surface calibrator. The temperature range can be used from 300 °C to 500 °C. The surface calibrator system was characterized by the evaluation of the surface temperature stability, surface temperature offset control, loading effect and repeatability. The measurement results showed that the temperature stability within 0.02 °C within 10 minutes after the furnace is stabilized. Through monitoring the reference surface temperature sensor, it was found that there is a (50 to 65) °C offset in the control system when the furnace is operated in the temperature range from 300 °C to 500 °C, and it shows a good linearity within the operation range. Loading effect was checked based on the surface temperature difference by comparing 1 and 2 surface probes loading and without loading of surface probe in the calibrator. This study indicated that 1.52 °C of the loading effect uncertainty should be added on in the final uncertainty evaluation if there are more than 1 surface probe which need to be calibrated simultaneously. With the analysis of the system measurement uncertainty, this novel surface calibrator system was suggested to put into calibration services for surface calibrator and surface probe calibrations.

Keywords: Surface calibrator, Surface probe, Heat pipe, Reference value, Temperature range

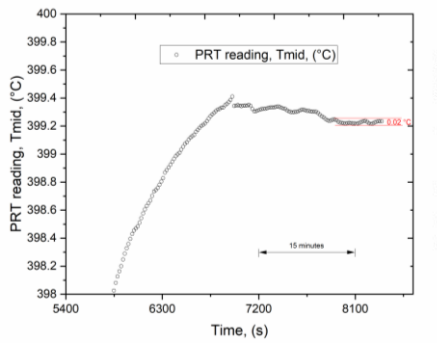

Fig.1. Stability monitoring using the middle reference PRT, T_{mid}

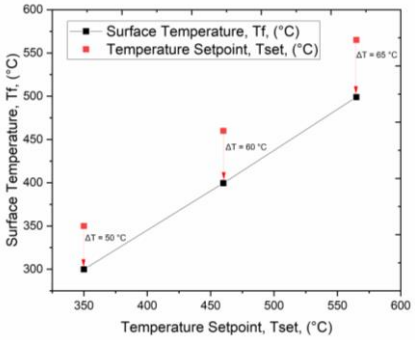

Fig. 2. Offset control of the surface calibrator

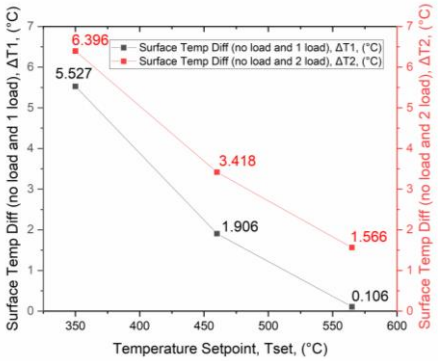

Fig.3. Loading effect analysis of the surface calibrator

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On the accuracy of surface temperature measurements with pipe clamp probes

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Special designs of contact thermometers are optimized for the measurement of temperatures on surfaces of solid bodies. Some of them can be applied on flat surfaces others are designed to be attached on curved surfaces, like on pipes. Due to design reasons, the temperature sensors of both types can't be set in ideal contact with the surfaces there are applied to, wherefore temperature measurement deviations arise. They depend on many influencing quantities like the design of the thermometer, the surface material and surface structure, the size of the contact area, the contact force and many others. Since this is well known, thermometers for application on flat surfaces were investigated in the past and calibration equipment was developed [1, 2, 3]. Pipe clamp probes can't be investigated at this calibration equipment since they have curved contact surfaces. Although they are widespread in use, such probes were not that much in the focus of interest. Hence, the authors focused on their investigation. For that, a calibration bench was built up allowing the investigation of probes on pipes with diameters from ½" to 2 (Fig.1)[4]. The pipes are flown through by saturated steam, which provides a very good heat transfer and a reproducible and homogeneous temperature distribution in the pipe. The steam temperatures are adjustable by means of pressure control in a temperature range from 100 °C to 150°C. Probes of different manufacturers were chosen arbitrarily and were analyzed using the calibration bench. It was found that the relative measurement deviations strongly depend on the probe design, thermal insulation, use of heat sink paste and other influencing factors. The measurement results are significantly deviating from the data provided in the probe data sheets which often are nontransparent or contain few information for the user. To improve that, a German guideline was issued which deals with the characterization of surface temperature probes, their calibration and calibration setups. The poster will deal with the calibration bench, results of measurements as well as the content of the guideline.

Fig. 1. Test bench for investigation of pipe clamp probes

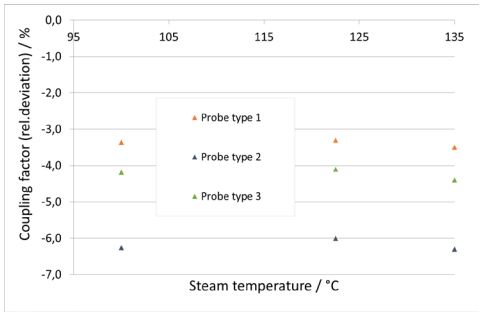

Fig. 2. Measurement error of different probe types at various steam temperatures

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Type 3 Non-Uniqueness in Standard Platinum Resistance Thermometers in the Temperature Range from 83 K to 353 K

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Type 3 non-uniqueness arises from differences between individual Standard Platinum Resistance Thermometers (SPRTs) over a given subrange specified by the International Temperature Scale of 1990 (ITS-90) because their resistance characteristics are not identical, and the interpolations cannot take the detailed differences fully into account. To assess the Type 3 non-uniqueness, the resistance of a cohort of SPRTs must be compared at several points over the required temperature range. However, such comparisons typically have uncertainties which are too large, and result in significant overestimation of the non-uniqueness.

This paper presents high precision comparisons of long-stem SPRTs carried out at National Physical Laboratory (NPL), Centro Espanol de Metrologia (CEM) and Istitut Niskich Temperatur I Badan Structuralnych (INTiBS). The measurements at each of the partners were as follows:

- NPL compared eight SPRTs in a stirred liquid bath in the temperature range from 178 K to 303 K
- CEM compared six SPRTs in a stirred liquid bath in the temperature range from 274 K to 353 K
- INTiBS compared six SPRTs in the temperature ranges from 198 K to 303 K and from 84 K to 185 K in a stirred liquid bath and a temperature-controlled cryostat, respectively.

The three cohorts of SPRTs were linked by two traveling SPRTs which were common to all of them to enable linkage. Using the calibrations of the SPRTs at the triple point of argon and at the freezing point of indium, the overall interpolation range could be extended down to 84 K and up to 429 K.

The Type 3 non-uniqueness is represented by the comparison differences for the specified ITS-90 interpolations, and for some alternative interpolation schemes. The results above 178 K show that the Type 3 non-uniqueness was no more than 0.1 mK between 178 K and 303 K and 0.2 mK up to 353 K.

A key fixed point of the ITS-90 is the mercury triple point, the use of which could be severely restricted or even banned by the UN Minamata Convention on Mercury [1]. Widely considered potential candidates for replacing mercury in a future amendment of the ITS-90 are the triple points of xenon (Xe), carbon dioxide (CO_2) or sulfur hexafluoride (SF_6). In this paper we summarize the measurements and describe the assessment of Type 3 non-uniqueness for interpolations in which mercury is replaced with the above fixed points. Further alternative interpolations using the melting point of gallium are also investigated.

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Least squares approach to standard platinum resistance thermometer subrange inconsistency reduction with redundant gallium and indium fixed points

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The International Temperature Scale of 1990 (ITS-90) defines several different and sometimes overlapping temperature subranges. Where overlap occurs, different definitions of the temperature t_{90} exist that have equal status but produce different results. This discrepancy is called type 1 non-uniqueness or subrange inconsistency (SRI).

In this paper, the SRI of the water-aluminum/water-zinc (SRI(Al:Zn)) and of the water-zinc/water-tin (SRI(Zn:Sn)) subranges of the ITS-90 were investigated for three cases. In the first case, the calculations followed the ITS-90 prescribed procedure. In the second case, the SPRT was calibrated at all fixed points of the subrange and its deviation function was then determined using the least squares method. In the third case, the least squares method was weighted by the uncertainties at each of the fixed points. One benefit of the least squares approach over exact interpolation is the reduction in uncertainty propagated from the fixed points. The calculations were applied to a large ensemble of 30 different SPRTs from the database of the Laboratory of Metrology and Quality at the University of Ljubljana, Slovenia. The sample consisted mainly of SPRTs manufactured by Fluke, Rosemount and AccuMac.

The difference in the mean and standard deviation of SRI(Al:Zn) for the three cases was small, amounting to less than 0.06 mK. On the other hand, the mean of SRI(Zn:Sn) decreased from 0.73 mK to 0.01 mK and the standard deviation decreased from 1.25 mK to 0.43 mK when the weighted least squares approach was applied. Furthermore, the total propagated error of the fixed points decreased in particular temperature ranges with weighted least squares, especially from 50 °C to 300 °C (by about 50% compared to the ITS-90 case) and to a lesser extent from 400 °C to 600 °C (by about 10% compared to the ITS-90 case). The contribution of the differences in the error propagation between pairs of subranges to SRI was estimated to be at least 50% in all cases. According to the presented results, it could be advantageous to calibrate the SPRT at all available fixed points in the selected temperature subrange and then determine its deviation function using the weighted least squares method.

SPRT stability as a limiting factor in the precision of interlaboratory comparisons

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The National Institute of Standards and Technology (NIST) acted as the pilot lab for a recent Key Comparison for Standard Platinum Resistance Thermometer (SPRT) calibrations at fixed points from the argon triple point through the zinc freezing point. Each participating lab was responsible for identifying and supplying two self-owned SPRTs to use as transfer standards for this comparison, with each SPRT being measured in the participant laboratory before sending it to NIST, then again once the SPRT returned form NIST.

Shifts in the measured SPRT resistance ratios at each fixed point, before and after measurement at NIST, were used to calculate a "transfer uncertainty" to account for handling and transport of the SPRT to and from NIST, as is standard practice. These shifts were also used to determine whether the SPRT was stable enough to contribute to the calculation of the Key Comparison Reference Value (KCRV). A surprising number of SPRTs failed the criteria for inclusion in the KCRV, indicating that comparisons at the highest level of precision may have reached a point where they are limited by the inherent stability of SPRTs.

In this poster we present data showing that SPRT stability may contribute in a meaningful way to comparison results such as this one, and that at some fixed points it may dominate the uncertainty of the fixed point itself.

A Bilateral comparison between CEM and INM on the calibration of SPRTs in fixed points in the range from 234.315 6 K to 933.473 K

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Aiming at providing support for the calibration and measurement capabilities of the Instituto Nacional de Metrología de Colombia (INM) in the range from 234.315 6 K (triple point of mercury) to 993.473 K (freezing point of aluminium), a bilateral comparison coordinated by the Centro Español de Metrología (CEM, Spain) was carried out during September 2018 and June 2020.

The transfer standards were three 25 Ω SPRTs one for the fixed points of Hg, Ga and Sn and two additional SPRTs for the Al and Zn point respectively. The thermometers had proven stability and were provided by INM, they showed a good stability during the performance of the comparison.

At first Zn point was not considered in the comparison but during preliminary results INM found a significant misbehave of the Sn point, thus it was agreed to repeat that point and that opportunity was used to include the Zn point as well.

This poster presents a summary of the main results of the comparison and the procedure to calculate the degrees of equivalence between the two institutes and the linkage to the related key comparisons.

Measurement of light-piping effect at the freezing point of silver using a high temperature standard platinum resistance thermometer (HTSPRT)

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The International Temperature Scale of 1990 (ITS-90) defines a number of fixed points, which are used for the calibration of high temperature standard platinum resistance thermometers (HTSPRTs) in accordance with the ITS-90. During the calibration of the HTSPRT, different uncertainty sources are present. At the temperatures above the freezing point of zinc (419.527 °C), the uncertainty due to the light-piping, caused by the radiation loss, becomes more and more dominant.

In this paper, a method for the measurement of the light-piping effect at the freezing point of silver using a HTSPRT will be presented. In the first case, the inner thermometer tube used inside the fixed-point cell will be practically without sandblasting on the outer surface. In the second case, the tube will be replaced with a sandblasted one that scatters the radiation and prevents excessive heat loss. In both cases, the silver freezing point cell will be compared with the reference cell, which was previously verified in the EURAMET.T-K 4 (EURAMET 820) interlaboratory comparison. The average temperature difference measured by the HTSPRT in the same fixed-point cell and in the two different inner thermometer tubes, one sandblasted and the other non-sandblasted, was 22 mK. This is in accordance with previously obtained light-piping simulation results [1].

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The stability of chip-size thermistors for miniature atomic clocks

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AIST/NMIJ has been developing miniature atomic clocks to increase the availability of accurate time references. The behavior frequency in a miniature atomic clock is known to depend on temperature [1]. Most main parts composing the atomic clock, such as a laser, a gas cell, and a photodetector etc. need to be packed in very narrow region, namely 10 mm × 10 mm × 10 mm [2], temperature control is conducted using a chip-size thermistor (0.6 mm×0.3 mm×0.3 mm, normal resistance R_{25}=100 kΩ). For obtaining a good prospect in a performance of miniature atomic clocks, therefore, the evaluation of the thermistor stability equipped on the main component is necessary.

In this study, we evaluated six chip-size thermistors selected from four different manufacturers. Thermistors were mounted on silicon oxide substrates forming thermistor assemblies as shown in Fig. 1. In order to see the effect of the stress, thermistors were mounted on the substrate by two methods with different amounts of solder. The resistance alternately between the triple point of water (TPW, 0.01 °C) and 80 °C. The stability of TPW was realized by a TPW cell, and the temperature of 80 °C in a typical operation condition of miniature atomic clocks, realized by an electric furnace combined with a standard platinum resistance thermometer that was calibrated following the International Temperature Scale of 1990.

Fig. 2 shows the resistance change of six thermistors (A, B, C, D is the manufacturers) over two months at the TPW. Between each pair of data points, there is one measurement at 80 °C. As shown in in Fig. 2, the resistance of the thermistor increases along with the increasing number of thermal processing, with degree of change to depend on the manufacturers. We will present details in this presentation.

This work was supported by Innovative Science and Technology Initiative for Security Grant Number JPJ004596, ATLA, Japan.

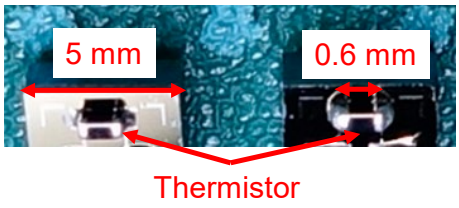

Fig. 1. Thermistors on silicon oxide substrates. (Left - method 1: small amount of solder, Right - method 2: large amount of solder)

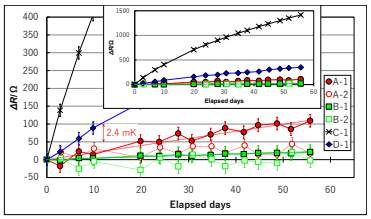

Fig. 2. Resistance changes of thermistors at the TPW. ” A, B, C, D “indicate the manufacturers of thermistor. “-1” and “-2” show the method number.

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A New Heat Pipe Standard Resistor Thermostat

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When using the DC/AC resistance ratio bridges, the temperature stability of the standard resistors as reference values plays an important role in measuring the resistances of the Standard Platinum Resistance Thermometers (SPRTs) to be used as interpolating instruments over the temperature range from 13.8033 K to 961.78 °C. As a result, the temperature variations of the standard resistors influence the accuracy of temperature measurements and the lever of realization of International Temperature Scale of 1990 (ITS-90). At present, the temperature-controlled oil baths or enclosures are used to keep the temperature of the standard resistors constant.

A new heat pipe technology was proposed to improve the temperature stability of the oil bath using the annular glass-water heat pipe. According to the working principle of heat pipes, they can attenuate the temperature fluctuations of the surrounding environment. Therefore, they are called temperature filters, a novel technology to be adopted at NIM. However, since the glass is too fragile to break, the application of the glass-water heat pipes to be temperature filters is very limited.

In order to apply the new technology for the standard resistors, a stainless steel-water heat pipe and corresponding temperature-controlled apparatus were developed at NIM. Also, the rugged container of stainless steel eliminates the breakage of the glass-water heat pipe. We will describe the new heat pipe thermostat for improve the temperature stability of the standard resistors, the obtained results and the effects of room temperatures on the stability of the standard resistors. The results indicate that the temperature stability within 15 hours is better than ±1mK, when the heat pipe thermostat operated at 20 °C. The abrupt changes of the environment temperature can influence the performance of the heat pipe thermostat. The more stable the room temperature, the better the temperature stability of the standard resistor. Therefore, heat pipe standard resistor thermostats can meet the requirements for the accurate measurements and are capable of substituting for the traditional maintenance oil baths for standard resistors.

From CCT-K7 to CCT-K7.2021: approaching the definition of the triple point of water temperature

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The temperature realized by a triple-point-of-water (TPW) cell is exactly 273.16 K only for the ideally pure Vienna Standard Mean Ocean Water (V-SMOW) [1]. In reality, the water enclosed within a TPW cell neither has an isotopic composition identical to the V-SMOW water nor is it ideally pure. Our understanding of the behavior of TPW cells has evolved since the first paper on the dissolution of the borosilicate glass envelope in 1997 [2]. As a result, the realization of the TPW temperature is continuously improving, approaching the ideal.

The first CIPM Key Comparison of TPW cells, CCT-K7, was carried out in 2002-2004 [3]. One of the major observations in CCT-K7 was the bimodal distribution of the results because 3 out of 21 participating labs had their TPW realization based on V-SMOW water which resulted in “warmer” national realizations (applying isotopic correction) compared to the rest of the participants. The TPW cells using the ocean water definition were 73 μK above the CCT-K7 key comparison reference value (KCRV). In addition, all the transfer cells used in the comparison were made from borosilicate glass and several of them had drifted during two weeks of measurements by more than 50 μK. This was likely caused by the impurities caused by the gradual dissolution of the glass envelope.

The successor of CCT-K7, CCT-K7.2021, was carried out in 2021-2022. As expected, in CCT-K7.2021 most participants renewed their national reference ensembles with newer, higher quality and vitreous-silica cells and applied the isotopic corrections to their respective national references. This, in turn, lead to: 1) the smaller spread of the national realizations, 2) only slightly asymmetric distribution of the results, and 3) the increase in KCRV value compared to CCT-K7 (closer to V-SMOW definition). We estimated the change of the KCRV between CCT-K7 and CCT-K7.2021 using the internal intercomparison results available from several participants.

Overall, the results of the CCT-K7.2021 suggest that the temperature community has reached a very good understanding of the behavior of TPW cells and associated uncertainties.

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The CCT Task Group on Digitalization

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The International System of Units (SI) lies at the core of global infrastructure providing confidence in the accuracy and comparability of measurements across a vast range of human endeavours. As the activities of industry, academia, governments and civil society increasingly undergo digital transformation, so too must the SI that underpins them.

To this end, the Consultative Committee for Thermometry Task Group on Digitalization (CCT-TG-Dig) was established in February 2022. The initial purpose of the TG was to support the Digital SI efforts, within the purview of CCT, of the Bureau International des Poids et Mesures (BIPM). The initial Digital SI objectives for the BIPM were to ensure machine-readability of the SI Brochure, its associated *Mises en Pratiques*, and further key documents of the Consultative Committees.

As such, the general objectives of CCT-TG-Dig are to:

- identify information that should be machine readable in the documents related to the *MeP-K*, such as the ITS-90 text, Guide, appendices, etc.; and
- recommend an indexing and archiving approach for the documents.

This poster will describe the initial tasks of the CCT-TG-Dig, review the progress made during its first year of existence, indicate possible future activities and outline the foreseen lifecycle for the future of the Task Group.

Forty years of sealed samples of CO_2 at IMGC-CNR since the measurement of its triple point as a possible replacement for the triple point of Hg in the ITS-90

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Since the 1970's the IMGC-CNR started research on accurate fixed-point calibration of cryogenic thermometers, and carbon dioxide was included among the substances that were permanently sealed in metal cells, according to a technique developed at IMGC-CNR since 1976, apt for measurement inside cryostats.

The first cell of carbon dioxide, CO_2, CO2-1 was sealed in 1977 and measured since 1978. The calorimeter then available had shown already to be of sufficient quality for this type of measurements according to the results obtained with argon and oxygen cells. Since then, 11 cells were sealed in different cell models with samples of CO2, of different purity (no isotopic composition available), some after distillation or containing a catalyst, until 2001. Of them, nine still exist and, based on the IMGC-CNR/INRiM experience with all cells containing samples of other gases, one can be confident that the quality of the sealed sample has remained unchanged over time (since 1986 the cell seal is of a strictly-permanent type developed and internationally patented by IMGC-CNR). Five are still stored at INRiM (from 2006, previously at IMGC-CNR), one was provided in 1989 to an Italian University, then three cells of the latest set were provided in 2001 to PTB, KRISS and NMI-VSL. Measurements were performed at IMGC-CNR between 1978 and 2001 (only one was published so far, in 1981 in the frame of a bilateral comparison between IMGC-CNR and PRMI).

This paper reports a summary of those measurements. An increase of the instrumental precision was either due to the increasing expertise at IMGC-CNR on the sample treatment, or a higher quality of the used calorimeters, and also on the increasing purity of the sample. The mean value obtained in 1977-79 with cells CO2-1–CO2-3 and CO2-5 has been $T_{90} = 216.592_9$ K, while with Cell CO2-4 it was $T_{90} = 216.589_3$ K. The temperature value obtained in 1989 with cell CO2-7 has been $T_{90} = 216.591_3$ K, while in 2000 using cell CO2-8 it was found to be $T_{90} = 216.592_3$ K. The last published measurements at NMIJ, reported in 2019 a value of $T_{NMIJ,90} = 216.590_9$ K, and in 2020 for a long stem cell $T_{NMIJ,90} = (216.590_9 \pm 0.000_{36})$ K (k= 1). In 2022, at VNIIM it was found $T_{VNIIM,90} = (216.591_7 \pm 0.000_3)$ K by using a method closely similar to the one used for the TPW cells. At NIM, in early 2023, a value $T_{NIM,90} = (216.591_{36} \pm 0.000_{37})$ K was found by using a long stem cell.

Develop a new optimized procedure for the updated argon triple point system

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The triple point of argon (TP-Ar) was accepted by the CCT in 1975 and replaced the boiling point of oxygen [1]. Since the first experiments carried out to determine the conditions and define their temperature value, several cryostats have been developed over the years [1-2]. The result of numerous investigations has made it possible to commercially have systems to the realization of this fixed point. One of them is the K38 model designed by Pond Engineering Laboratories Inc [3]. Basically, this portable system has the advantage that a few liters of liquid nitrogen are enough to realize and maintain the TP-Ar, reaching the value of -189.34 °C [4].

The thermodynamics department of the National Institute of Industrial Technology (INTI) acquired the K38 in 2006 extending ITS-90 scale realization to the TP-Ar. Since its acquisition until 2016, tests have been carried out with the aim of defining a procedure that would allow optimal operation to reproduce stable plateaus. In 2017 due to transport problems, this system suffered irreversible damage. In 2021, the K38 was returned to the laboratory after its respective repairs and upgrades. Consequently, the initial methodology to realization of the TP-Ar was updated to the current model and a new measurement procedure was developed.

The results and differences obtained in the reproducibility values between the original K38 version and the updated one are shown. In addition, heat flow measurements at different immersion depths are discussed.

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A Closed-Cycle Immersion Cell Platform for Noble Triple Points

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We have developed a new closed-cycle refrigeration platform for the storage, condensation, freezing and controlled melting of noble gas solids for direct realization of their triple point (TP) temperatures in an immersion-type cell. The system accommodates long-stem standard platinum resistance thermometers (SPRTs) through a single 7.75 mm inner diameter thermowell that is continuously purged with helium gas and thermally coupled to four separate control zones and strongly coupled to the noble-gas solidus.

The system design incorporates several features that were originally found in a legacy argon system designed by Furukawa [1] which was used at NIST for more than 30 years prior to it's decommissioning. In contrast, this new patented design [2] is based on two commercial single-stage Stirling cryocoolers and does not utilize liquid nitrogen for maintaining the melt conditions. Active cooling is applied to the first two control zones via the two cryocoolers while two other inner zones are passively cooled and actively controlled via heating only. The Stirling coolers are soft-mounted using bellows connections and thermally coupled to the two outermost zones via flexible copper wire-rope straps which serve to decouple vibration transmission from the Stirling's linear motors operating at 60 Hz.

The cell holds approximately 210 mL of noble condensate, either argon, krypton or xenon, and the integral expansion ballast volume of 21 L is sufficient to keep pressures below 10 bar at ambient conditions. The gas manifold provides both pressure and mass flow rate regulation and is capable of controlling the rate of gas condensation and monitoring the rate of gas expansion as the system changes temperature. A single vacuum chamber encloses the four nested control zones and the cell. Testing has been conducted using a set of diagnostic diode thermometers located on each of the zones. Initial results indicate the system is suitable for Xe and Kr TP realizations but that additional refinements in the thermal strap configurations are needed to support Ar TP realizations.

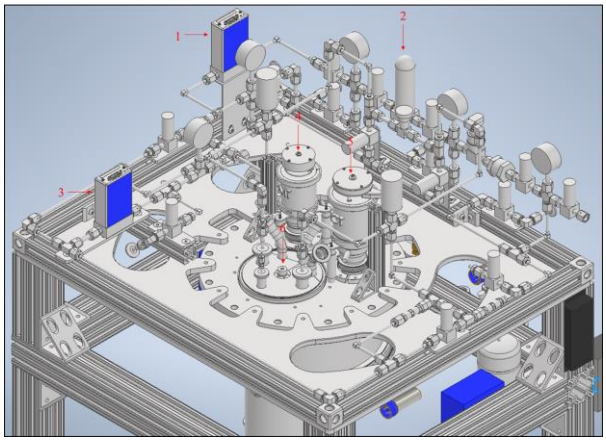

Fig. 1. A rendering of the platform viewed from above.

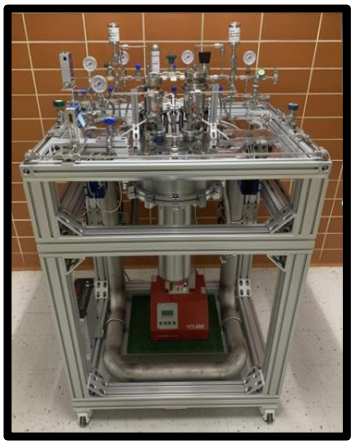

Figure 2. The noble triple point realization platform.

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Construction and evaluation of gallium point cells

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Gallium melting point is one of the fixed points of the international temperature scale of 1990 (ITS-90) for calibrating a standard platinum resistance thermometer (SPRT) [1]. The melting point of gallium (29.7646 °C) is realized using a gallium point cell that has high reproducibility and stability. This is one of advantages of using the gallium point for calibrating SPRTs to be used at near room temperature.

We here in AIST/NMIJ developed gallium point cells based on 7N nominal purity of gallium [2-3]. In this study, we constructed new two gallium cells using different purity of gallium samples for the purpose of evaluating the influence of different samples and different cell structure on the gallium point realization. The structure of new cells is as shown in Fig.1. The crucible was made from PTFE and enclosed in a quartz glass cylindric container. A quartz glass re-entrant well is placed in the center of the PTFE crucible guided by a PTFE liner which is fixed to the PTFE lid, so that a direct contact between the quartz re-entrant well and the gallium sample is avoided. The distance from bottom of the well to liquid surface was 153 mm. The pressure in the cell was controlled to be 1 atm using 6N of argon gas. We evaluated the repeatability of the realized gallium point realizing temperature the effect of hydrostatic pressure and the gas pressure to the realized gallium point using the new cells. Comparisons between the new cells and the national standard cell [2] that has different construction from the new ones are also reported.

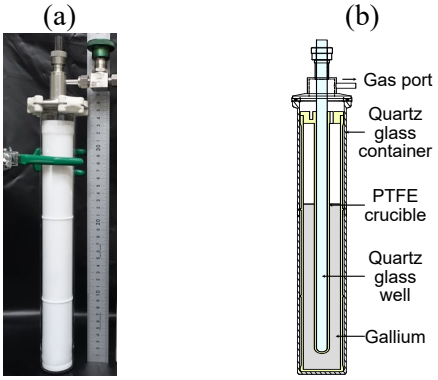

Fig. 1. Structure of the new gallium point cell.
(a): actual appearance, (b): schematic diagram

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Manufacture and evaluation of a new zinc reference standard cell of Inmetro

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The National Institute of Metrology, Quality and Technology (Inmetro) in Brazil has employed fixed-point cells as reference standards to calibrate thermocouples and standard platinum resistance thermometers (SPRT), reproducing the International Temperature Scale of 1990 (ITS-90)[1]. The zinc freezing point (419.527 °C) is among the 17 fixed-points defined by ITS-90. Inmetro has been seeking to improve its techniques for building fixed-point cells and for this purpose has built some cells over the last few decades. As a continuity of this initiative, an open zinc freezing point cell was built using high purity zinc (99.9999%), it was named INM Zn2019-01.

This work outlines the details of the construction process of the INM_Zn2019-01 cell manufactured at Inmetro, including the materials used, constructive characteristics, manufacturing method, melting and freezing curve evaluations, as illustrated in Fig. 1, cell thermal profile analysis an metal purity assessment. A comparison with other cells manufactured by Inmetro and by renowned manufacturers is also carried out, and finally the determination of a correction and an uncertainty to the temperature of the cell, as demonstrated in the Table 1.

Additionally, using published results of international comparisons, including the CCT-K9 [2], it was also possible to compare the performance of the manufactured cell with the ones from other national institutes, and it was possible to demonstrate that the performance of this new cell is compatible with the ones used as national temperature standards. In face of the good results presented by the INM Zn2019 01 cell, it was considered the Inmetro zinc reference standard.

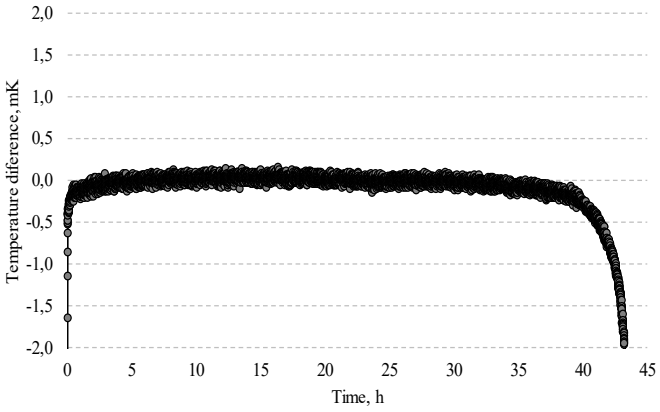

Fig. 1. INM Zn2019-01 freezing Plateau

Table 1. Study of the temperature differences between the Inmetro's Zinc cells

	Cell	ΔT (Ct - Ref) mK	$u_{\Delta T}$ (k=2) mK
Ref. (LN)	LN 742879	0.0	2.2
Cells under teste (Ct)	EPC 027	-2.4	2.3
	INM Zn01	-0.9	2.3
	INM Zn02	-1.7	2.3
	INM Zn2008-01	0.1	2.2
	INM Zn2019-01	-0.1	2.2

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Acoustic gas thermometry and thermodynamic temperature measurement at KRISS

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We report measurement results of thermodynamic temperature by acoustic gas thermometry at KRISS between −40 °C and 120 °C. A quasi-spherical resonator made of copper with the nominal inner diameter of 50 mm was used in this work. The speed-of-sound in high-purity argon gas in the resonator was measured by measurements of acoustic resonance frequencies with a combination of measurements of microwave resonance frequencies while the pressure of the argon gas was controlled by two mass flow controllers. In each isothermal condition, the speed-of-sound at ten different pressures between 150 kPa and 600 kPa was measured in order to estimate the speed-of-sound at zero-pressure. For an acoustic measurement, maximum eleven radial resonance modes were analyzed, while for simultaneous microwave measurements, three lowest TM modes were measured for an in-situ evaluation of the average effective inner radius of the resonator. Isotherms at twelve temperatures between −40 °C and 120 °C including the triple points of mercury and water, and melting point of gallium were taken while two capsule-type standard platinum resistance thermometers were used to compare the measured thermodynamic temperature with the international temperature scale of 1990. The measurement below the room temperature was carried out in an ethanol bath that was cooled by liquid nitrogen flow in a heat exchanger. A water bath and a three-zone furnace were employed as thermostats for above room temperature. The standard uncertainty of the thermodynamic temperature measurement was below 3 mK for the temperature range between −40 °C and 120 °C. Our plan to extend the measurement range to lower temperature will be also presented.

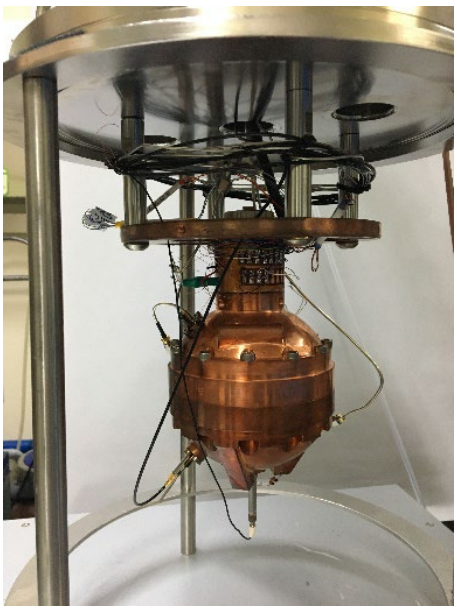

Fig. 1. The acoustic gas thermometer used in this work at KRISS.

T-T_{90} Measurements using Acoustic Gas Thermometer up to Gallium Point in Neon Gas

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The National Metrology Institute of Japan (NMIJ, AIST) started the work using acoustic gas thermometer (AGT) to measure the thermodynamic temperature and (T-T_{90}) by developing an AGT system that employs a prototype quasi-spherical resonator (QSR) using a low-cost machining, as already reported elsewhere [1]. Since then, a new AGT system was also developed by adopting a new QSR, which was fabricated using a diamond-turn tool to have better finishing of its internal surface [2]. To confirm that our AGT system is independent of the gas used, neon gas has been applied in our low-cost QSR to replace argon gas, which was usually used in our previous measurements.

The measurement using the AGT follows the principle as described elsewhere [3]. The AGT system used in this work consists of a one-liter QSR made of oxygen-free copper (OFC), a gas handling system, an acoustic measurement system and a microwave measurement system. To work on neon gas, the gas handling system including the entire tube connections has newly been constructed. The thermostatic bath, the acoustic and the microwave measurement systems employed in this work are those also used in our previous work [2]. Neon gas used was 5N nominal purity.

(T-T_{90}) has been measured at 10 ºC, 20 ºC and Ga melting point. Figure 1 depicts (T-T_{90}) currently available in the nearby temperature, showing that the present result agrees with the other reported values within the estimated uncertainty. We found challenges to solve when using this low-cost QSR: the temperature inhomogeneity across QSR and the improvement of the acoustic measurements. Extending (T-T_{90}) measurements to higher temperature range using this QSR is our next challenge. This work was partly supported by JSPS KAKENHI Grant Number 21H01346.

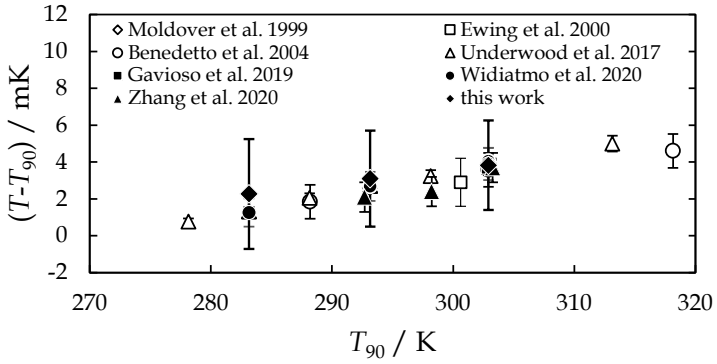

Fig. 1. Available (T-T_{90}) from AGT and the present result.

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Measurements of the Acoustic Virial Coefficients of Argon from 118 K to 323 K

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The speed of sound in a dilute monatomic gas such as argon is directly proportional to the square root of thermodynamic temperature. This physical fact forms the basis of primary acoustic gas thermometry (AGT). However, the speed of sound also has a pressure dependence due to intermolecular forces. For the same reason, the gas density is not exactly proportional to pressure at a constant temperature. This pressure dependence is commonly expressed as a virial expansion in powers of pressure or density.

Improvements in the accuracy of the virial coefficients of monatomic gases will benefit primary thermometry, in addition to having wider benefits to fluid metrology. For example, recent *ab initio* calculations of the helium potential have resulted in a drastic reduction in the uncertainty of the helium virial coefficients, which has resulted in a reduction in the uncertainty of primary dielectric constant gas thermometry (DCGT) [1], and opened the way for time-efficient, single state AGT [2], where the speed of sound is measured at a single pressure instead of multiple pressures on an isotherm. For argon gas, the uncertainty in *ab initio* calculations is currently larger than experiment over the temperature range of primary thermometers. More accurate argon virial data is desirable, since argon possesses some advantages over helium such as reduced sensitivity to impurities for AGT, and a greater polarizability for DCGT and refractive index thermometry. Improved *ab initio* calculations for argon are currently in progress, and high accuracy experimental results such as those reported here will be used to validate these calculations.

This work reports new experimental determinations of the second acoustic virial coefficients of argon in the temperature range from 118 K to 323 K. The values are derived from an analysis of speed of sound measurements performed by the author in a previous publication [3]. The speed of sound (u) measurements were conducted on isotherms spanning a pressure (p) range from 100 kPa to 500 kPa.

In AGT, the quantity of interest is the zero-pressure intercept in the $u(p)$ curve, meaning that the results are insensitive to systematic errors that are proportional to pressure. In contrast, the second acoustic virial coefficient is the linear term in the $u(p)$ curve, so special attention must be paid to quantifying and correcting for these errors. The most troublesome of these is the poorly understood shell recoil correction, which arises from the coupling of acoustic and mechanical modes within the resonator. Two independent approaches to this correction are investigated.

The results are compared with the existing experimental data, and with the most recent *ab initio* calculations.

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Plenary Session I: Temperature, Climate and Human Health

The Heat Index: What this "Feels Like" Temperature Tells us about the Future of Human Heat Stress
David Romps (University of California, Berkeley, USA); Yi-Chuan Lu (University of California Berkeley, USA)
Invited

Taking the Temperature of the Global Ocean
Sarah Purkey, Nathalie Zilberman and Dean Roemmich (UCSD, USA)
Invited

Invited

The Heat Index: What this "Feels Like" Temperature Tells us about the Future of Human Heat Stress

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The heat index is the apparent temperature, or "feels like" temperature, widely used to communicate the danger of heat and humidity. Defined in 1979 by physicist Robert Steadman, the heat index is based on a model of human thermoregulation, and each value maps to a unique state of human behavior and physiology. In particular, the heat index is the temperature, at a reference water-vapor pressure of 1.6 kPa, that would induce the same behavioral/physiological state as that induced by the actual temperature and humidity. Although weather agencies have relied on the heat index as a communication tool for decades, it has had two major deficiencies: the heat index was undefined in high heat and humidity and it was never validated against laboratory data.

The heat index was never defined in high heat and humidity because the underlying model of thermoregulation would give unphysical results in those conditions. In the 1970s, an undefined heat index was a rare event, but global warming is rapidly increasing the frequency of conditions that have an undefined heat index. Recently, the problem with the model has been identified and fixed, allowing the heat index to be defined for all temperatures and humidities [1]. That work has revealed that previous estimates of the heat index – arrived at by extrapolation – were biased low during severe heat waves. For example, during the 1995 Chicago heat wave, the heat index was underreported by 17 °F [2].

The heat index was also never validated against laboratory data. A major reason for this is that the heat index had been undefined in the kinds of extreme heat and humidity that tend to generate the most easily measured consequence of heat stress: hyperthermia. Using laboratory data from Larry Kenney's group at Penn State, it is now possible to compare the predictions of the heat-index model against the physiological responses of human subjects. The results show that the heat-index model makes very accurate predictions of the onset of hyperthermia [3].

Global warming's exacerbation of heat waves poses a direct threat to human health. Many previous studies of these future impacts have relied on the dry-bulb temperature or the wet-bulb temperature, but neither of those is particularly well-suited as a proxy for heat stress. The existence of a well-defined and validated heat index in the climate-science toolbox opens a new path to evaluating the future of human heat stress.

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Invited

Taking the Temperature of the Global Ocean

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The oceans are the largest sink of anthropogenic warming, absorbing ~89% of the Earth's energy imbalance [1]. Since the early 2000s, this additional heat has been measured using data collected through the international Argo program, a global array of roughly 4000 autonomous robotic profiling floats each measuring the ocean temperature and salinity from 2 km to the surface every ten days. Argo's ability to produce climate quality observations that allow for accurate and precise estimates of the month-to-month variability in ocean heat content on regional to global scales such as those produced for the annual state of the climate [1] [Figure 1], is contingent on two factors. First, Argo requires high accuracy and stability of its sensors during the averaged float lifetime of 5.5 years with some deployed for over 10 years. At present, Argo floats primarily use the SeaBird Electronics SBE41 conductivity-temperature-depth (CTD) sensor designed for applications in the upper 2km, with temperature, salinity, and pressure accuracies (stabilities) of 0.002°C (0.000°2 C/year), 0.0035 psu (0.0011 psu/year) and 2 dbar (0.8 dbar/year), respectively. Second, the spatial and temporal resolution of Argo sampling needs to be adequate to resolve the heterogeneity of ocean warming, sampling the full-depth global ocean. At present, the largest error in ocean heat content estimates is due to under sampling. A continuous renewal of the Argo array is required to sustain the Argo dataset and avoid any spatial gaps, allowing for continuation of the long-term time series. Decreasing the error estimates in ocean heat content in the future requires expanding coverage in regions of higher climate variability and sampling the full ocean volume. Deep Argo, a new type of Argo float capable of sampling to 6 km, can now sample 99% of the ocean volume, and carries a new CTD from SeaBird Scientific with even higher accuracy [Figure 2]. The implementation of a global Deep Argo float array will improve estimates of the deep-ocean ocean heat content in addition to providing additional measurements of the upper-ocean. Here we will assess the evolution of the past, current, and future requirements of temperature observations from Argo to fully track regional and global ocean heat content.

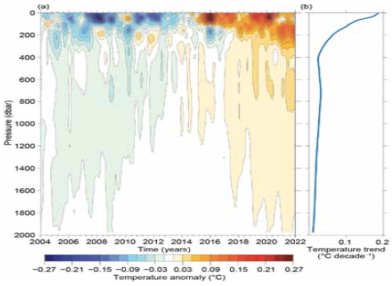

Fig.1. Global monthly ocean temperature anomalies measured from Argo floats from [2] following the method of [3] .

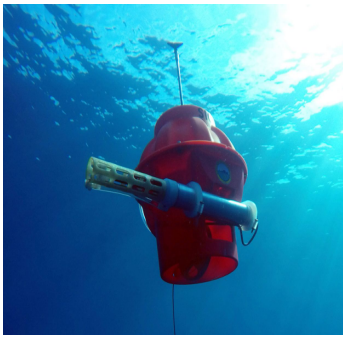

Fig. 2. Deep Argo, a new type of Argo float capable of sampling from the surface to 6 km, with the more accurate SBE 61 CTD. Image from [4]

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Parallel Session J1: Triple Point of Water

Applying Different Analysis Methods to CCT-K7.2021 Key Comparison
Andrea Peruzzi (National Research Council, Canada); Sergey Dedyulin (National Research Council of Canada, Canada); Antonio Possolo (National Institute of Standards and Technology, USA)

Comparison of Triple-point-of-water cells at KRISS
Inseok Yang (Korea Research Institute of Standards and Science, Korea (South))

Investigations on the Triple Point of Water by Means of a Cryogenic Current Comparator
Martin Goetz (Physikalisch-Technische Bundesanstalt (PTB), Germany); Lars Buenger, Dieter Heyer, Eckart Pesel and Steffen Rudtsch (Physikalisch-Technische Bundesanstalt, Germany)

Drift Behavior of the Old Triple Point of Water Cells
Xiaoke Yan (National Institute of Metrology (NIM), China); Steffen Rudtsch (Physikalisch-Technische Bundesanstalt, Germany); Zhejian Meng (China Jiliang University, China); Ping Qiu and Jintao Zhang (National Institute of Metrology, China); Yuning Duan (National Institutue of Metrology (NIM), China)

Applying Different Analysis Methods to CCT-K7.2021 Key Comparison

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The Mutual Recognition Arrangement (MRA) drawn up in 1999 by the International Committee of Weights and Measures (CIPM) is based on key comparisons (KCs) of national measurement standards, carried out by the National Metrology Institutes (NMIs) that quantify the agreement between the values measured by the NMIs in the form of degrees of equivalence (DoEs). The DoE of a national measurement standard is the difference between its measured value and the key comparison reference value (KCRV), and the expanded uncertainty (for 95% coverage) associated with this difference [1].

As consequence, the determination of the KCRV value (and its uncertainty) from the KC measurement results is a fundamental exercise in the reduction of data from every KC. Unfortunately, beyond a general statement about the role intended for the KCRV, as a close approximation of the true value of the quantity of interest, there is no CIPM guidance about how to determine the KCRV. Owing to this lack of guidance, the choice of the KCRV in many Consultative Committee for Thermometry (CCT) KCs has been made at the cost of time-consuming and often inconclusive discussions among the participants (see, for example, CCT-K3 [2]).

We applied and compared different analysis methods to the results of a recent major thermometry KC, the CCT-K7.2021 KC of triple-point-of-water cells, with the goals of 1) providing the CCT community with a short review of the analysis methods available in the literature, 2) illustrating the peculiarities of the different analysis methods in a practical, worked-out example, 3) discussing the choice of the method eventually selected for the analysis of CCT-K7.2021, and 4) reflecting on the meaning of the KCRV (consensus value vs best approximation of the true value) and dark uncertainty.

The analysis methods we applied to CCT-K7.2021 results were: Procedure A in [3], Largest Consistent Subset [4], Pooled Probability Distribution [5], Maximum Likelihood [6], Leave-One-Out [6] and two methods, the Adaptive Weighted Average and the Hierarchical Gauss + Gauss procedure, which are implemented in the NIST Decision Tree (NDT) [7]. The NDT is a web application that guides the user through a series of statistical tests (mutual consistency of the measurement results, and symmetry and normality of the measured values), with the goal of helping the user decide on an appropriate statistical model and statistical procedure for the reduction of the measurement results provided by the user. When applied to the CCT-K7.2021 data set, the NDT recommended to apply the *adaptive weighted averag*e, AWA, (which is the well-known DerSimonian-Laird procedure). The Bayesian Hierarchical Gauss + Gauss was also applied as an additional investigation of the presence of dark uncertainty.

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Comparison of Triple-point-of-water cells at KRISS

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Twenty-four full size triple-point-of-water (TPW) cells were compared in 2021-2022 against the national reference TPW cells of Korea. The cells were compared partly as a measurement campaign at KRISS for the CIPM key comparison CCT-K7.2021. The set of cells, which includes three national reference cells, was composed of 8 fused-silica cells and 16 borosilicate cells, among which some of the old cells were manufactured as early as 1982. On each day of comparison, typically four or five cells were measured in a batch. The measurement on a day was closed by the measurement on the first cell of the day, and the result was validated only when the two measurements on the same cell was within 30 µK. The uncertainty of the comparison on a single measurement of temperature difference ΔT were 14 µK (with a coverage factor $k = 1$).

Figure 1 shows the measured ΔT from the national reference of KRISS sorted by the realized temperature in descending order. The temperature differences ΔT were distributed from +28 µK to −297 µK. Total of 11 cells, which include all national reference cells, were within ± 30 µK (indicated as horizontal dashed lines in Fig. 1). The result indicated a weak correlation between ΔT of the cell and the repeatability in the daily measurements of ΔT. Even with the same ice mantle, the standard deviation of the daily-measured ΔT of a cell with $\Delta T < -30$ µK was higher than the standard deviation of the cells that were closer to the national reference. This implies that chemical impurities, which are considered as source of large $|\Delta T|$ of the TPW cell, also worsen the temperature repeatability of the cell.

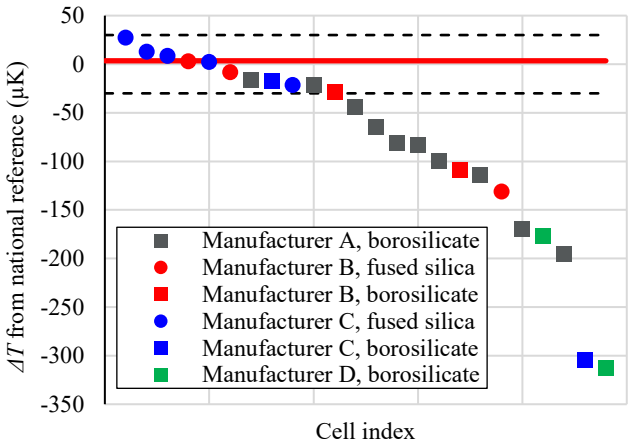

Fig. 1. Measured temperature difference of the triple-point-of-water cells from the national reference of KRISS.

Investigations on the Triple Point of Water by Means of a Cryogenic Current Comparator

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Cryogenic Current Comparator (CCC-)based measurement bridges are used for the most demanding measurements in resistance metrology. For example, in the calibration of a 100 Ω standard resistor against the Quantum Hall Resistance standard, the achievable measurement uncertainty is as small as a few parts in 10^9. The unsurpassed performance of CCC-bridges suggests applications in certain resistance thermometry measurements, namely those where extremely small changes of temperature shall be resolved.

An example are studies of the influence of hydrostatic pressure on temperature measurements in a triple point of water (TPW) cell with a standard platinum resistance thermometer (SPRT). A first experimental investigation including the use of an especially designed CCC-bridge has been published by Nakanishi and Sakurai in 2005 [1]. It motivated the experiments reported in this contribution.

We used a commercial transportable and highly flexible measurement bridge with a CCC developed at the Physikalisch-Technische Bundesanstalt (PTB). It has altogether 18 windings including a subset with numbers of turns according to powers of 2 from 1 to 2048 ("12bit-CCC"). This allows to adapt the bridge configuration easily to the resistance of a given SPRT: measurements with two thermometers having resistances at TPW of 25.40 and 25.76 Ω, respectively, have been successfully performed. We have used commercial metal-sheated long-stem SPRTs connected with a shielded cable. The standard resistor used as the reference has been placed in a metallic enclosure, too. This was sufficient for operating the bridge in a conventional thermometry lab – further efforts with respect to electromagnetic shielding have not been necessary. Throughout we have used a well-known thermal stabilized standard resistor of nominal value 10 Ω as the reference in our measurements. The TPW cell wherein the temperature has been measured by means of the SPRT was loaded to a commercial maintenance bath. According to an Allan variance analysis of a long-term SPRT vs 10 Ω-measurement (50 hours) with a current of ±100 µA flowing through the SPRT, the type-A uncertainty after one hour is as small as 50 pV corresponding to a temperature resolution of about 2.5 µK (all values refer to coverage factor k=1). A custom-made support enabled the reproducible variation of the SPRT's immersion depth into the thermometer well of the TPW over a range of 100 mm. Our experimental results are in agreement with the earlier finding by Nakanishi and Sakurai that the corresponding ITS-90 value underestimates the effect of tic pressure in a TPW cell.

In conclusion, the essential items of the setup – TPW and maintenance bath, a suitable SPRT and a CCC bridge (including reference resistor) – are commercially available and found in a number of national metrology institutes worldwide, often within very short distance. We explicitly encourage closer collaborations between resistance metrology and resistance thermometry in the context of CCC application. Obviously, a potential re-evaluation of the hydrostatic pressure coefficient of TPWs could be in the focus of such activities. Other interesting topics will be identified, too.

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Drift Behavior of Old Triple Point of Water Cells

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The triple point of water (TPW) is the most important defining fixed point of the International Temperature Scale of 1990 (ITS-90). Therefore, it plays a prominent role in guaranteeing the reproducibility and reliability of the ITS-90.

The TPW is realized in the cells made of borosilicate or fused silica envelopes. Due to the slow dissolution of glass by means of leaching and etching processes, the impurities from glass containers can dissolve into the water, resulting in the increase of the impurity concentration in the water. As a result, the impurity-induced temperature depressions with ages were observed in the old TPW cells. According to the Hill's findings, some cells remained stable for many years, while others decreased with increasing ages of the cells. At present, this is a mystery about the TPW cells, because only 2 borosilicate glass cells kept at NRC appear to have no long-term drift. The glass materials and pre-leaching using different acids before filling water into the glass containers are main factors attributable to the long-term stability of the TPW cells.

In order to study the long-term drift of the old TPW cells to uncover the mystery, a joint investigation was undertaken at NIM and PTB to compare the TPW cells with different ages. After preparation of the ice mantles in the cells, the continuous measurements of the resistances of standard platinum resistance thermometers (SPRTs) in the cells were made until the observed temperatures were stable for at least ten days. Through the comparisons between the old cells and the newly manufactured reference cells, the drift behavior of cells with different ages were determined. Due to the diffusion of impurities from the water outside the ice mantle, some old cells need 15 days to be stabilized within 0.1mK. Therefore, for the international key comparison of TPW cells, the protocol requirement that the ice mantles should be aged at least 7 days is not accurate to eliminate the long-term drift of the old cells when using the old cells for the participants. Also, the average long-term drift rate of the borosilicate cells was obtained using the linear model. According to the NIM comparison results, the average long-term drift rate of the old cells with manufacturing dates from 1974 to 2003 is -11.8μK/yr. It is very close to those of -14.5μK/yr of the PTB old cells and -13μK/yr of the NIST.

Moreover, the immersion characteristics of a SPRT in the cells were investigated to determine the hydrostatic pressure correction coefficients of the TPW cells. The values obtained from the old cells are obviously different from the recommended value of -0.73 mK/m. Therefore, for the old cells, it is very necessary to use the experimental correction coefficients to reduce the hydrostatic pressure effects. Corresponding reasons were given using the Clapeyon relation.

The temperature-controlled capacitance-conductivity apparatus was used to monitor the long-term drift of the cells. According to the NIM experiment results, the fitted slope of temperature depression versus turn-over frequency is -13.3 μK/kHz.

Parallel Session J2: Radiation Thermometry II

Long term stability of an InGaAs radiation thermometer
Li Wang (National Metrology Centre, ASTAR, Singapore); Yan Fan (National Metrology Centre, ASTAR, Singapore)

High Temperature Fibre-Optic Infrared Radiation Thermometry
Matthew J Hobbs (The University of Sheffield, United Kingdom (Great Britain)); Jon R Willmott (University of Sheffield, United Kingdom (Great Britain))

Low Uncertainty Thermodynamic Temperature Above the Silver Point Using Relative Primary Radiometry
Dave Lowe and Graham Machin (National Physical Laboratory, United Kingdom (Great Britain))

Non-Uniqueness of ITS-90 Above the Silver Point and Determination of T - T90
Peter Saunders (Measurement Standards Laboratory of New Zealand & Industrial Research Limited, New Zealand)

Long term stability of an InGaAs radiation thermometer

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Calibration of radiation thermometers at a set of fixed-point blackbodies and interpolation of output signals according to Planck law is a very useful method to approximate ITS-90 below the silver or copper temperatures. Working wavelength of 1.6 μm and an InGaAs detector are common choices if the intended temperature measurement range is down to the indium point. Besides other parameters affecting the performance of the thermometer, such as Size-of Source (SSE), non-linearity, spectral responsivity, signal amplification, etc., the long-term stability is a major factor. Good long-term stability minimizes the need for frequent calibration at the fixed-points, and it gives users confidence in the reliability of measurement using the radiation thermometer. NMC set up an InGaAs radiation thermometer and fixed-point blackbodies facilities from indium to copper in 2008, and the thermometer has been calibrated against the fixed-point blackbodies regularly since. The calibration results over about 14 years are summarized and analysed to obtain the long-term stability of the thermometer. In this paper, the NMC InGaAs thermometer and the fixed-point blackbodies are described, and the long-term stability of the thermometer is presented.

Keywords: Radiation thermometers, Fixed-points, fixed-point calibration and interpolation, Long-term stability

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High Temperature Fibre-Optic Infrared Radiation Thermometry

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Non-contact temperature measurements using infrared radiation thermometers (IRTs) are widely used within industrial processing applications to optimise material quality and process efficiency. For specific applications, where it may not be possible to sight the IRT upon the target, fibre-optics (FOs) are used to couple the emitted infrared radiation to the infrared detector. Whilst such instrumentation is ubiquitous within industrial processing applications, there are many further applications where their usage would provide considerable benefit, but they are not currently implemented due to a reliance on traditional methods. In this work, we explore two such applications which utilise FO-IRTs for inherently high temperature measurement scenarios.

Confined blast loads are traditionally characterised with the use of some form of pressure gauge. We demonstrate a new approach to blast load characterisation, utilising a FO-IRT to measure the temperature of a fireball during its early stages as it develops and expands within a confined blast load. With a response time of 4 µs and an RMS noise of ±0.5 K at circa 1700 K, we were able to measure the temperature within a confined blast load as the fireball during its early stages [1]. Our FO-IRT is capable of measuring fireball temperatures from circa 800 K to beyond 5000 K, with a nominal field-of-view of 2:1.

Thermocouples are the traditional temperature measurement technique used within embedded temperature measurement scenarios; the maximum temperature at which specialist silica-based FOs are rated is circa 600 ºC. We demonstrate a sapphire FO-IRT for the measurement of temperatures up to 900 ºC for embedding within a cutting tool, and up to 1200 ºC when embedded within nickel alloy test sample [2]. The sapphire FO-IRT was found to have a measurement error within ±2 ºC or ±0.25% of the target temperature, therefore comparable or better than the equivalent thermocouple technology.

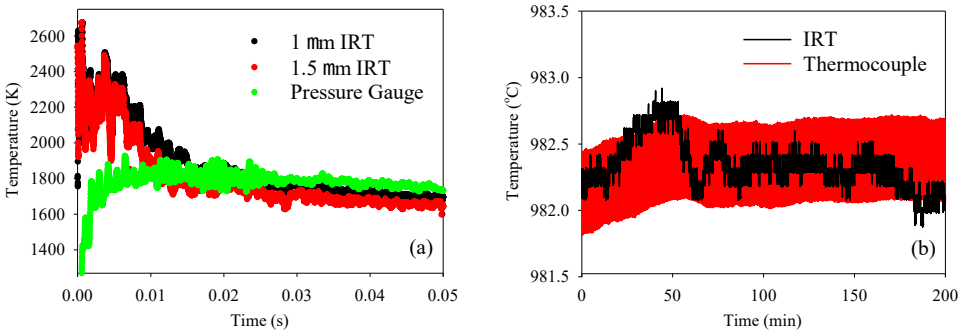

Fig. 1. (a) Confined blast load IRT temperature measurement in comparison to pressure gauge and (b) high temperature sapphire-based FO-IRT target temperature drift measurement in comparison to thermocouple.

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Low Uncertainty Thermodynamic Temperature Above the Silver Point Using Relative Primary Radiometry

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The *mise-en-pratique* for the definition of the kelvin (*MeP*-K-19) has given the possibility of relative primary thermometry with uncertainties competitive with the ITS-90 at temperatures above the silver freezing point [1]. High temperature fixed points (HTFPs, [2]) for use as temperature references have temperatures and uncertainties assigned based on the best absolute primary radiometry. These can be used as the basis of an interpolated thermodynamic temperature scale. This yields thermodynamic temperature independent of any particular formulation. As part of the EMPIR project Real-K[1] [3] – thermodynamic temperatures are being assigned to the HTFPs of Fe-C, Pd-C, Ru-C and WC-C. Using a radiometer with a thermodynamic temperature range from 1400 K to over 3000 K NPL tested different combinations and numbers of HTFPs for relative primary radiometric thermometry ultimately settling on a calibration using the n=2 scheme [1] using Cu and Re-C. Here we give a full description of how thermodynamic temperature was established together with the uncertainty evaluation. The approach provides access to thermodynamic temperature. We compare this realization of thermodynamic temperature to that of the individual evaluation of HTFP thermodynamic temperature values of Co-C, Pt-C and Re-C (measured in earlier work) [4] and in so doing show that relative primary thermometry achieves uncertainties equal to or lower than absolute primary radiometry (Fig. 1). This work shows that besides establishing direct traceability to the kelvin we also demonstrate that this is more easily and robustly achieved than its equivalent ITS-90 approximation.

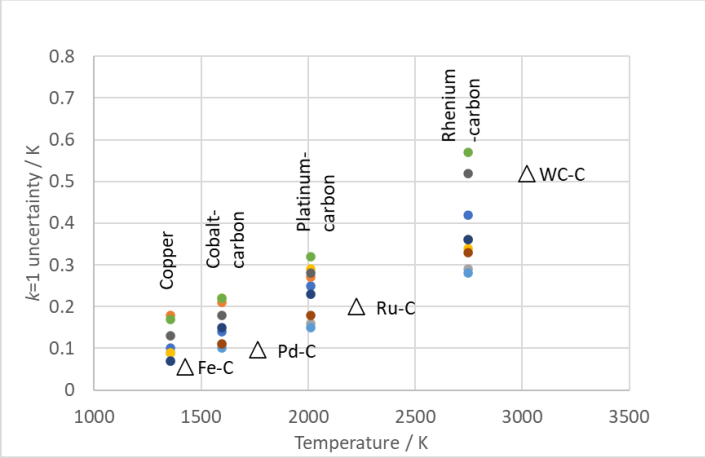

Figure 1 Circles show previous state-of-the art primary radiometry uncertainties at fixed points of Cu, Co-C, Pt-C and Re-C [4]. Triangles show the uncertainties achieved for relative primary radiometry at the fixed points of Fe-C, Pd-C, Ru-C and WC-C.

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Non-Uniqueness of ITS-90 Above the Silver Point and Determination of $T - T_{90}$

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Non-uniqueness is a fundamental limit to the reproducibility of a defined temperature scale. In this presentation, the non-uniqueness of temperatures, T_{90}, on the International Temperature Scale of 1990 (ITS-90) above the silver point is fully investigated.

The non-uniqueness arises from three causes: inconsistency in extrapolation with the choice of the three allowable ITS-90 reference fixed points; a wavelength dependence of T_{90} due to the difference between thermodynamic temperature, T, and T_{90} at these reference fixed points; and a further wavelength dependence arising from the discrepancy between the value of the second radiation constant defined on ITS-90 and its value derived from fundamental constants.

The non-uniqueness is quantified by deriving an exact expression for $T - T_{90}$ above the silver point and calculating the differences in this expression as a function of reference fixed point and wavelength. In the worst case, the non-uniqueness is about 100 mK, and $T - T_{90}$ is as much as 400 mK, at 3000 °C. Uncertainties in the $T - T_{90}$ differences are also derived, and it is shown that it may be possible to determine T above the silver point from a laboratory's existing ITS-90 scale with lower uncertainty than a primary radiometric determination using a single fixed point with known thermodynamic accuracy.

Parallel Session J3: Thermocouples I

Drift of conventional type N and dual wall type N mineral insulated metal sheathed thermocouples in isothermal and thermal cyclic conditions
Michele Scervini (& ISOMIL GmbH, Germany)
Invited

An improved methodology for the measurement of the insulation resistance of MIMS thermocouples at high temperatures: the time-dependent behavior of the insulation resistance
Michele Scervini (& ISOMIL GmbH, Germany)

Refractory Metal Thermocouples at 350-2315°C
Todd Leonhardt (Rhenium Alloys Inc., USA); Herb Dwyer Dwyer (Nanmac Corp, USA); Christopher A. Thom, Joe Johnson and Sam Belsito (Rhenium Alloys Inc., USA)

Invited

Drift of conventional type N and dual wall type N mineral insulated metal sheathed thermocouples in isothermal and thermal cyclic conditions

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This paper describes the behaviour of mineral insulated metal sheathed type N thermocouples in both isothermal and thermal cyclic conditions at high temperatures. In particular two different thermocouple configurations were studied: a conventional type N thermocouple and a dual wall type N thermocouple. The latter was developed at the University of Cambridge and its lower drift compared to conventional thermocouples was already reported in previous publications. The data in this piece of work not only confirm the improved drift performance of dual wall thermocouples in isothermal conditions, but expands considerably the knowledge on the behaviour of type N sensors in thermal cyclic conditions which produce in type N conventional thermocouples a much more pronounced drift compared to isothermal conditions. On the contrary the dual wall type N thermocouples do not seem to be affected or are affected only to a limited extent by thermal cyclic conditions and they retain the good performance shown in isothermal conditions. The test campaign explored the behaviour of sensors at temperatures between 1150°C and 1300°C. After drift tests in isothermal and thermal cyclic conditions at 1150°C selected sections of conventional and dual wall type N mineral insulated metal sheathed thermocouples have been subjected to metallurgical analysis. Using advanced microscopic techniques with an electron microscope the change in elemental content was measured across the positive and negative thermoelements of the type N thermocouples. The more significant increase in the level of contamination experienced by conventional type N thermocouples can be related to their increased drift compared to standard dual wall thermocouples, whose composition changes only to a very limited extent. Furthermore, the results allow to rationalise the effect of the operating conditions on contamination and drift: thermal cyclic conditions produce higher level of contamination compared to operation in isothermal conditions and with more severe thermal cycles the change in composition is more pronounced. These observations correlate well with the results of drift tests which have demonstrated a more intense drift in thermal cyclic conditions compared to an isothermal exposure.

An improved methodology for the measurement of insulation resistance of MIMS thermocouples at high temperatures: the time-dependent behavior of the insulation resistance

Michele Scervini

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The current methodology suggested by technical standards for the assessment of the insulation resistance of thermocouple cables at high temperatures relies on the use of a high voltage source between the wires or between a wire and the sheath of the sensor. Such a methodology is suggested by technical standards to test the insulation resistance at both ambient temperature and high temperatures. In this paper the author argues that an alternative methodology based on the use of a current source is preferable for the measurements of insulation resistance at high temperatures. The new methodology was applied in this work to measure the insulation resistance of type K thermocouples between 800°C and 1300°C. Long term tests in both isothermal condition and thermal cyclic conditions were undertaken: this allowed to identify a time-dependent change of the insulation resistance at high temperatures, a phenomenon that had not been previously reported in the literature. Concurrently the test campaign allowed to comment on the insulation breakdown and its frequency when thermocouples operate at high temperatures for prolonged time.

Refractory Metal Thermocouples at 350-2315°C

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Rhenium Alloys Inc. performed a comprehensive metallurgical study of the chemical, physical, and electrical properties of ultra-high temperature type C thermocouples before, during, and after exposure to high temperature in a hydrogen environment to understand the limitations of high temperature measurement techniques. Our experiments were performed in a Spectra-mat furnace capable of reaching 2200°C in a pure hydrogen atmosphere. To compare the temperature as measured by the thermocouples, we also utilized an optical pyrometer with a quartz viewing window in the furnace bell (Fig. 1). All runs were conducted with 2 adjacent thermocouples composed of W5Re/W26Re wires, molybdenum sheaths, and ceramic insulators made of either alumina (Al_2O_3), hafnia (HfO_2), boron nitride (BN), or beryllium oxide (BeO). Each run had a nominal temperature ranging from 700°C (1292°F) to 2200°C (3992°F), as measured by the pyrometer. However, our data reveal significant deviations between adjacent thermocouples, as well as the optical pyrometer (e.g., Fig. 2).

To investigate the possible root cause of the disagreement, we examined all thermocouple components with optical microscopy and scanning electron microscopy-energy dispersive spectroscopy. Our analyses show decomposition reactions between the various components and microstructural changes to the wire after exposure to high temperature, both of which could explain the observed changes in the thermocouple properties. Further work is needed to reconcile the results obtained from different thermocouple assemblies and to develop best practices in understanding the limitations of high-temperature measurement techniques.

Fig. 1. Spectra-mat furnace with optical pyrometer, thermocouples, and data logger.

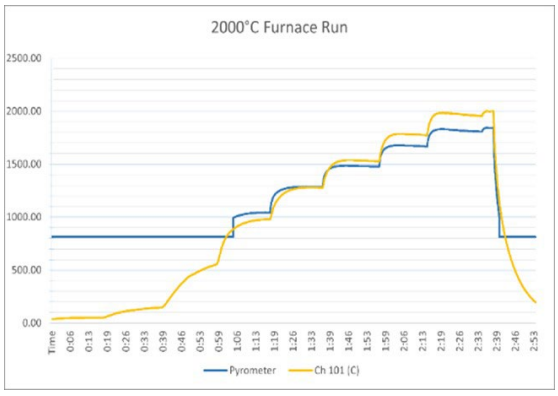

Fig. 2. Optical pyrometer (blue) versus thermocouple data (yellow) for a nominally 2000°C run.

Parallel Session J4: Air Temperature for Meteorology and Aviation

A validated multi-physics model of a meteorological instrument shelter
Jonathan Pearce (NPL, United Kingdom (Great Britain)); Laura G Bevilacqua (National Physical Laboratory, United Kingdom (Great Britain)); Robin Underwood and Stephanie Bell (NPL, United Kingdom (Great Britain))

Metrological characterization of climate reference station thermometers
Peter Pavlasek (Slovak Institute of Metrology); Milan Ioan Maniur (Slovak Institute of Metrology, Slovakia); Graziano Coppa and Chiara Musacchio (Istituto Nazionale di Ricerca Metrologica, Italy); Andrea Merlone (INRiM, Italy)

Design of a setup for reproducible calibration of air thermometers
Åge Andreas Falnes Olsen (Postboks 170 & Justervesenet, Norway); Peter Rothmund, Karsten Opel, Jan-Erik Holmen and Reidun Anita Bergerud (Justervesenet, Norway)

Evolution of Total Air Temperature (TAT) Sensors
Bob E Sable (Collins Aerospace & Rosemount Aerospace, USA)

A validated multi-physics model of a meteorological instrument shelter

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It is well known that temperature sensors used for meteorological and other applications are subject to errors from ambient thermal radiation influences such as direct sunlight and clear night skies [1] and need to be screened accordingly [2]. The World Meteorological Organization (WMO) has encouraged the development of analytical and numerical models for the assessment of radiation screen performance [3]. To model a realistic thermal and atmospheric environment for assessing the thermal performance of meteorological temperature sensors and to guide their optimization, a three-dimensional steady-state model of a meteorological instrument shelter was set up using COMSOL Multiphysics® 6.0. The model geometry is based on a widely used 'Stevenson screen' design with double louvres, and it is a replica of an actual screen at NPL employed to enable experimental validation of the model. The "heat transfer in solids and fluids", "surface-to-surface radiation" and "turbulent flow" interfaces were used, which incorporate all conductive and convective heat transfer within and between solids and liquids, turbulent fluid flow, and surface-to-surface radiation between almost all surfaces. All physics interfaces were coupled. The screen is surrounded by air which enters the model with a specified airspeed and temperature (boundary conditions at the inlet) and flows out of the model on the opposite side, representing the wind. The ground above which the screen stands was also modelled, and it also participated in radiative heat exchange with the screen.

The purpose of the model is to provide information on typical temperature distributions and airflow patterns within the screen, which can be used for more rigorous modeling of methods for overcoming the radiation-induced temperature measurement errors commonly reported in this type of measurement.

Following a description of the model, we report the progress on overcoming two key challenges associated with modeling radiative heat transfer. The first is to determine, and incorporate in the model, the spectral emissivity of the screen (and other) surfaces. The second is to approximate radiative heat exchange between the screen, ground and sky, particularly at wavelengths between 8 μm and 14 μm where the atmospheric absorptivity is low. Modeling this is very challenging because the radiative properties of the sky depend on a huge number of factors such as pollution, humidity, geographic location, time of day, azimuth and elevation. As the aim of the model is to assess the 'worst case' where radiative heating of the temperature sensors is most significant, and because of the extreme additional complexity involved, clouds are ignored.

We also report on a preliminary validation of the model by comparison with temperature measurements throughout the real screen (inside and out) and in the ground. The exterior wind speed and direction, as well as the incident solar irradiation, have also been measured in order to match the ambient modelled and measured conditions. Ultimately, the validated model will be used to assess various strategies for overcoming radiative temperature measurement errors inside meteorological screens.

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Metrological characterization of climate reference station thermometers

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Ground-based stations are an essential part of a complex climate observing systems which purpose is to generate data for evaluating local and global climate trends. Measurement traceability in these types of stations is fundamental for generating a robust climate understanding based on comparable data in space and time, both within networked stations and between networks. This importance was expressed by the Global Climate Observing System (GCOS) of the United Nations Environment Programme and WMO (World Meteorological Organization), in its published report 226 that highlights the need for available reference grade observations for accurately detecting of local and global climate trends [1]. As a following action, the GCOS launched in 2022 the implementation plan of its Surface Reference Network (GSRN) where an essential part of the effort is the understanding of instruments performance in field monitoring of temperature, humidity, and pressure. We focused the work here presented on the characterization of resistance thermometers of various types that are candidates to be installed in future prototype reference station. The selection of sensors using resistance measurement principle was motivated by their overall frequent in field use and general superior performance in comparison to other commonly used temperature sensors. The measurements took place under controlled laboratory conditions simulating as close as possible conditions in the field, leading to recommendations on the requirements of instrumentation for a climate reference station. In order to properly determine sensor performance and the components of the measurement uncertainty budget for climate reference stations the metrological parameters as stability, hysteresis and self-heating were determined. These essential parameters were measured in a temperature range typical for air temperature measurements for climate which is from -40 °C up to +60 °C. The characterization of temperature sensors from multiple manufacturers has shown diverging results in all measured parameters which were measured over the whole temperature range. In general, the measurements indicate that from the point of sensor stability the critical temperatures were 20 °C and -40 °C, with indicated highest temperature instability on the level of 0,02 °C. The highest hysteresis effect has been observed at temperatures of 0 °C and -40 °C with a maximum of 0,05 °C. Sensor self-heating exhibits multiple dependencies of the level of supply current that vary with tested sensor and temperature point. This research was made possible thanks to the project (19SIP03- Climate Reference Station) which has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme. This work is part of the opening activities for a future GSRN affiliated research facility.

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Design of a setup for reproducible calibration of air thermometers

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A European interlaboratory comparison (ILC) for comparing methods of air thermometer calibrations was launched in 2019. The comparison was organized in three loops with 7 or 8 thermometers circulated within each loop. Justervesenet (JV) acted as the link laboratory, and developed a flexible, stable setup for calibration of sensors in air, where the most important design constraint was to ensure comparability between the three loops.

The design consists of a purpose-built inner chamber that fits inside a commercial climate chamber, with a volume large enough to accommodate any of the circulating probes. The chamber consists of two concentric cylinders separated by a gap of around 10 mm. The inner cylinder, which encapsulates the probes under test, has a perforated bottom with meticulously placed holes to allow controlled air flow into the measuring volume. A stable flow is established quickly, from around 10 cm above the bottom. The air speed is controlled by a fan placed at the top, whose rotation speed is controlled with a motor placed outside the main climate chamber, coupled to the fan via a long shaft. This ensures that heat generated by motor is not interfering with the air temperature control. Temperature and humidity controlled air is fed into the gap between the cylinders. The setup homogenizes the air flow in the measuring volume and ensures consistent conditions for all probes. Furthermore, a rigid support helps to ensure a reproducible placement of both sensors under test and reference sensors. Under operation 7 reference probes were used in various locations in the measuring volume, and 2 sensors placed in the wall of the inner chamber.

The walls are constructed from aluminium, which provides a good compromise between machineability, cost, weight and thermal properties.

We present here the results of extensive characterization of the setup, including the temperature uniformity, flow conditions, and the effect of self-heating on the reference probes in various locations inside the chamber. We claim that the setup provided the necessary stability and performance to justify the loop linkage with JVs measurements.

Evolution of Total Air Temperature (TAT) Sensors

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Total Air Temperature (TAT) has been an important aircraft measurement for more than 60 years. TAT is the maximum temperature which can be obtained by 100% conversion of the kinetic energy of flight. It is the Static Air Temperature (SAT) plus the heat due to the compression of the air described by the aircraft moving. See Equation 1 [1] and Fig. 1 for the relationship between TAT and SAT.

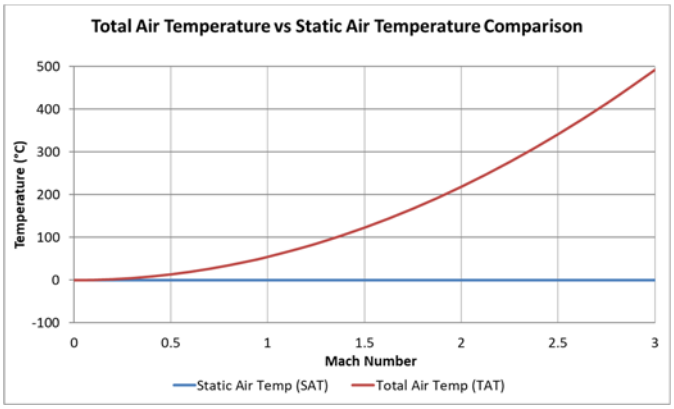

Fig. 1. TAT vs SAT Comparison.

$$TAT = SAT * (1+.2 * (M^2))$$

Where:
M = Mach number
TAT = total air temperature in °R or K
SAT = static air temperature in °R or K

Equation 1. Total Temperature [1].

$$TAS = M * (38.96695 * \sqrt{} (TAT / (1+.2 * (M^2))$$

Where:
TAS = True airspeed in knots
M = Mach number
TAT = total air temperature in °R or K

Equation 2. True Airspeed.

TAT is critical for aircraft as it is needed to compute the True Airspeed (TAS), as shown by Equation 2. TAS is used by many aircraft systems, such as the Automated Flight Control System, Autopilot System, Autothrottle and Flight Guidance. TAT is also critical for proper engine performance as it's an input to the Full Authority Digital Engine Control (FADEC). Depending on the engine, TAT is used for engine control and condition monitoring, determining proper fuel flow, scheduling of inlet guide vanes, control of fan speeds and engine pressure ratio selection.

Since the mid-1950's, Rosemount Aerospace has been continually evolving the TAT design. To improve dry air measurement, performance in liquid water and ice crystal icing conditions, response time or durability, TAT designs have gone through many changes. The newest XDTAT® sensor can meet the latest regulatory requirements while providing excellent TAT performance in all flight conditions. See Fig. 2 for the TAT sensor evolution.

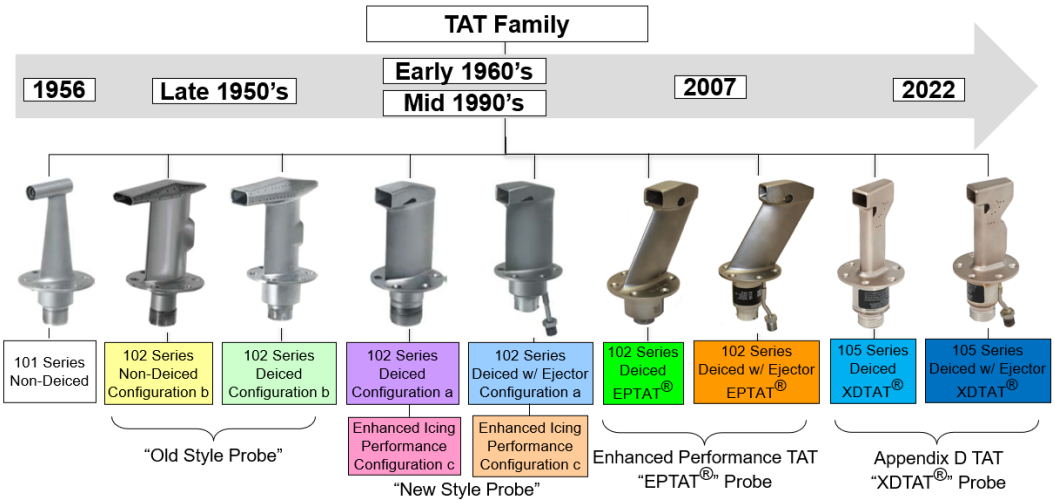

Fig. 2. TAT Sensor Evolution.

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Parallel Session K1: Thermodynamic Temperature II

Relative thermodynamic temperature over the whole temperature range
Mohamed Sadli and Laurent Pitre (LNE-Cnam, France); Stephan Briaudeau (LNE-INM/CNAM, France); Frédéric Bourson (LNE-Cnam, France); Fernando Sparasci (Laboratoire Commun de Métrologie LNE-Cnam, France)
Invited

New T-T90 data from 5 K to 24.5 K by single-pressure refractive-index gas thermometry
Bo Gao (Technical Institute of Physics and Chemistry of the Chinese Academy of Sciences, China); Haiyang Zhang (The Technical Institute of Physics and Chemistry of the Chinese Academy of Sciences, China); Xiang-Jie Kong, Yao-Nan Song and Ercang Luo (Technical Institute of Physics and Chemistry of the Chinese Academy of Sciences, China); Laurent Pitre (LNE-Cnam, France)

Invited

Relative thermodynamic temperature over the whole temperature range

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Now that the definition of the kelvin offers the possibility of realizing and disseminating the temperature unit in various ways including thermodynamic temperature, it is time to weigh the pros and cons of the different possibilities offered in terms of practicality, uncertainties, and possible responses to emerging needs.

This presentation will summarize the capabilities developed at LNE-Cnam over the last decade to put in practice thermodynamic temperature measurement methods at the lowest and the highest temperatures of the covered range, namely 10 mK to 3000 K.

In the high temperature range, above 1300 K, the measurement of thermodynamic temperature by a radiometric method was performed using a radiance comparator associated to a radiance-meter, with a particular emphasis on the understanding of the optical effects occurring in the experimental set-up. This method and its uncertainties were validated during the international determination of the thermodynamic temperature of several high-temperature fixed points in 2016 [1,2]. We will show how efficient this method is, although it is difficult to realize on a routine basis compared to the use of relative thermodynamic temperature in this range in agreement with the Mise-en-Pratique of the kelvin at high temperature.

In the low temperature part, below 300 K, the measurement of the Boltzmann constant performed in 2017 [3] with the lowest uncertainty world-wide allowed the group to develop skills in acoustic gas thermometry and to exploit them in developing new methods for absolute or relative thermodynamic temperature measurement. A review of these possibilities will be given including the possibility of extrapolating T below 24 K using the speed of sound or the Lorentz-Lorenz equation and below 1K by with the Curie-Weiss law applied to specific paramagnetic materials.

Addressing new needs and challenges relating to quantum technologies is one of the objectives assigned to our group. Following the pioneering work performed at NIST [4] on primary quantum thermometry using optomechanical resonators, our group has led a European joint research project (JRP “PhotOQuanT”) to develop such quantum optomechanical technology [5]. This research is continuing in the frame of a national-funded project in close collaboration with two major French laboratories (Kastler Brossel - University of Sorbonne and C2N-CNRS) to further develop and study quantum optomechanical sensors. The thermomechanical noise thermometry results obtained so far will be presented as well as the near-future orientations towards telecom wavelengths.

Finally, we will describe the way we expect to realize and disseminate the thermodynamic temperature in France over the next decade and how we think it will be possible to bridge the gap between the low-temperature range and the high-temperature range to realize thermodynamic temperatures.

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New $T–T_{90}$ data from 5 K to 24.5 K by single-pressure refractive-index gas thermometry

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In our previous work [1], we used ^{4}He-based single pressure refractive-index gas thermometry (SPRIGT) to measure $T–T_{90}$, the discrepancy between thermodynamic temperature and that of ITS-90, after re-definition of the kelvin. The values obtained at temperatures from 5K to 24.5K had uncertainties $u(T)$ better than 0.17 mK. In this work, we describe improvements to the SPRIGT system and we provide new values of $T–T_{90}$ in the same temperature range. The compared results indicate that the improved SPRIGT system is robust, with excellent repeatability, reliability and stability. First, as before, the uncertainty of T is less than 0.17 mK. Second, good reproducibility of T_{90} was observed via three calibrated rhodium-iron resistance thermometers (RIRTs), with differences never exceeding 0.06 mK. Third, the $T–T_{90}$ results of two runs separated by 2.5 years, run10 in [1] and run19 in this work, have good agreement, with most of the differences $\Delta(T–T_{90})$ better than 0.07 mK. The maximum value of $\Delta(T–T_{90})$ is no more than 0.10 mK, which is only 0.9 times its standard uncertainty. Nowadays, our previous $T–T_{90}$ data [1] has been used by CCT-WG-CTh to develop a smooth analytic function for describing the best estimate of $T–T_{90}$ as a function of the measured scale temperature T_{90} [2]. In the next step, our $T–T_{90}$ and T data will be used for thermometer calibration and international comparison of thermodynamic temperature via RIRTs or home-made platinum cobalt resistance thermometers.

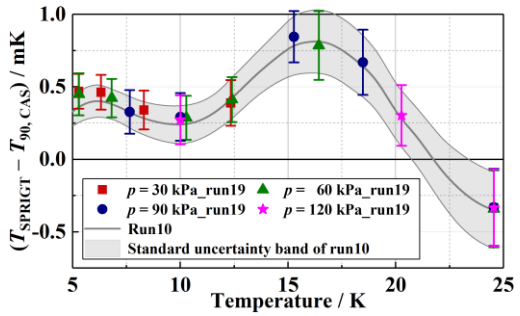

Fig. 1. Comparison of $T–T_{90}$ for the SPRIGT method for two runs separated by an interval of 2.5 years. Lines: thick line, $T–T_{90,CAS}$ determined in our previous work [2] (Table 9, run10); thin lines, standard uncertainty of $T–T_{90,CAS}$, $u(T–T_{90,CAS})$. Symbols and error bars: $T–T_{90,CAS}$ and $u(T–T_{90,CAS})$ determined in the present work (run19) at different isobars (30, 60, 90, 120) kPa.

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Parallel Session K2: Satellite-based Earth Temperature Monitoring

The next generation thermal infrared satellite in-flight radiometric calibration sources
Daniel M Peters (STFC UKRI, United Kingdom (Great Britain)); Tim Nightingale and Frauke Izdebski (STFC, United Kingdom (Great Britain)); Jonathan Pearce (NPL, United Kingdom (Great Britain)); Radka Veltcheva (National Physical Laboratory, United Kingdom (Great Britain)); Christian Monte (Physikalisch-Technische Bundesanstalt, Germany); Max Reiniger (PTB, Germany); Albert Adibekyan (Physikalisch-Technische Bundesanstalt, Germany)

Spaceborne Radiance Temperature Standard Blackbody for the Chinese Future Benchmark Satellite
Xiaopeng Hao and Jian Song (National Institute of Metrology, China); Yuning Duan (National Institutue of Metrology (NIM), China); Zundong Yuan (National Institute of Metrology, China)

Miniature water and gallium-indium fixed-point cells for in-situ thermometry calibrations in space
Radka Veltcheva (National Physical Laboratory, United Kingdom (Great Britain)); Jonathan Pearce (NPL, United Kingdom (Great Britain)); Daniel M Peters (STFC UKRI, United Kingdom (Great Britain))

Landsat 9 Thermal Infrared Sensor 2 (TIRS-2) Radiometric Calibration and Potential Future Landsat Thermal Band Efforts
Matthew Montanaro (NASA Goddard Space Flight Center & Rochester Institute of Technology, USA); Joel McCorkel, Aaron Pearlman, Boryana Efremova, Brian Wenny, Allen Lunsford, Dennis Reuter, Jason Hair and Murzy Jhabvala (NASA Goddard Space Flight Center, USA)

The next generation thermal infrared satellite in-flight radiometric calibration sources

Daniel M. Peters[1], Dave Smith[1], Tim Nightingale[1], Frauke Izdebski[1], Jonathan V. Pearce[2], Radka I. Veltcheva[2], Albert Adibekyan[3], Max Reiniger[3] and Christian Monte[3]
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Satellite measurements in the thermal infrared are an essential tool in monitoring the Earth's climate, predicting weather and scientific research in Earth observation. They require stable calibration source(s) in-flight to correct for instrument self-emission and allow radiometric calibration that is traceable to the SI. To date thermal infrared in-flight calibration sources use some form of electrical thermometer combined with a high emissivity surface to allow radiometric calibration using Planck's law [1]. Once launched instrument re-calibration traceable to the SI is currently not possible.

The traditional space industry launches large climate class instruments they are conservative in the application of new technologies as the cost of launch is high. To fly new technology requires significant effort to reduce risk and ensure a very low failure rate in-flight. In this paper, we outline three new technology developments that will enable high performance in-flight calibration with well characterized uncertainties which are insensitive to thermometer drift [1].

Key technology developments include new thermometer readout electronics, high emissivity coatings and ITS-90 [2] in-flight traceability. These activities have been funded by the UK Space Agency via the Center for Earth Observation Instrumentation (CEOI) during the Next Generation Infrared Target (NGenIRS) project.

NGenIRS was demonstrated by comparison of the emitted radiance at the PTB Reduced Background Calibration Facility 2 with PTB reference sources [3]. Funding was part of the Far-infrared Outgoing Radiation Understanding and Monitoring (FORUM) Phase AB development with Airbus for the ESA Earth Explorer 9 program.

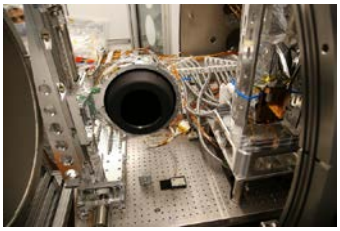

Fig. 1. Photo of the RAL Space NGenIRS calibration target installed at the PTB facility.

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Spaceborne Radiance Temperature Standard Blackbody for the Chinese Future Benchmark Satellite

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The spaceborne radiance temperature standard blackbody (SRTSB) combined with a series of miniature phase change fixed points (MPFPs) for temperature calibration and emissivity verification by a thermal radiation loop (TRL) is developed as a radiance temperature standard source for a high precision infrared remote sensor of Chinses future benchmark satellite at National Institute of Metrology, China (NIM). The MPFPs of the SRTSB contain the H_2O, Ga, alloy Ga-Sn and Phenyl Salicylate. The TRL is used to measure the emissivity of the spaceborne blackbody based on the control of environmental radiation. The experimental results show that the emissivity of the blackbody is higher than 0.998, and the temperature control stability is better than 5 mK. The temperature control uniformity at the bottom and the axial are better than or equal to 11 mK and 38 mK between the working temperature range from 268.15K to 331.15K, respectively. The repeatability of the MPFPs is less than 5 mK, and the results of the continuous phase transition of the MPFPs are in obvious temperature plateau. The extended uncertainty of the SRTSB is lower than or equal to 0.084 K (k=2).

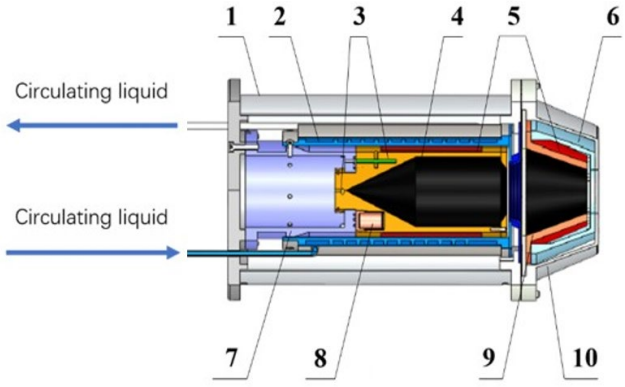

Fig. 1. Cross-sectional schematic of the spaceborne radiance temperature standard blackbody. 1-outer shield, 2-temperature control cover, 3-thermometer, 4-cavity, 5-heater, 6-insulation cover, 7-insulation structure, 8-MPFP, 9- TRL, 10- Outer shield

Miniature water and gallium-indium fixed-point cells for *in-situ* thermometry calibrations in space

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Satellite-borne radiometric measurements of the earth's surface are very challenging [1] and rely on on-board blackbody cavities at known temperatures to provide *in-situ* calibration of the radiometers. These blackbodies must themselves be traceably calibrated, which can be difficult to maintain because the thermometers on board (which are typically platinum resistance thermometers) tend to exhibit calibration drift, and the calibration uncertainty required is approximately 20 mK or lower. Hence in some applications it is desirable to have on-board calibration of the thermometers.

Miniature phase-change cells are of growing interest for this task and can be made very small while still retaining adequate metrological performance [2,3]. In previous work [2], NPL and RAL Space have developed a miniature phase-change cell using approximately 2 g of gallium, melting point 29.7646 °C.

This paper describes the further development[1] of similar sized cells using approximately 0.5 g of water (melting point 0 °C) and approximately 3.4 g of a eutectic alloy of gallium and indium (Ga-In eutectic, composition approximately 19.7 % indium by weight, melting point approximately 15.7 °C, as widely reported in the literature[2]). These two materials provide additional calibration points over the temperature range of interest. The stainless-steel cell container has a length of 20 mm and a diameter of 8 mm. The internal volume has a length of 18 mm and a diameter of 7 mm, giving an internal volume of approximately 0.7 cm^3.

These phase-change cells are intended to be embedded in the aluminum flight-ready calibration blackbody structure, adjacent to the platinum resistance thermometers used for temperature monitoring and control, for the purpose of *in-situ* calibration of those sensors. This presents additional measurement challenges, because the thermometers cannot be immersed directly in the miniature fixed-point cell.

For this study the miniature phase-change cells were embedded in a surrogate blackbody structure (a block of aluminum) and Pt100 thermometers were embedded in bores adjacent to the cells. For the cells containing both water and Ga-In it was possible to produce clearly defined melting curves with a duration of several hours, and repeatability of about 20 mK. We describe some early results, and discuss some practical considerations associated with realizing such small fixed-point cells.

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Landsat 9 Thermal Infrared Sensor 2 (TIRS-2) Radiometric Calibration and Potential Future Landsat Thermal Band Efforts

Matthew Montanaro[1,2], Joel McCorkel[1], Aaron Pearlman[1,3], Boryana Efremova[1,3], Brian Wenny[1,4], Allen Lunsford[1,5], Dennis Reuter[1], Jason Hair[1], Murzy Jhabvala[1]
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The Thermal Infrared Sensor 2 (TIRS-2) instrument on Landsat 9 provides the latest generation of thermal infrared Earth observations for the Landsat program. Routine thermal band measurements began in 1982 with Landsat 4 and its single-channel design and evolved in 2013 to a dual-band design with the TIRS instrument on Landsat 8, thereby improving derived surface temperature accuracy [1]. The TIRS-2 instrument is a near-copy of the TIRS design but with expanded electronic redundancies to prevent single point failures and modifications to address a major stray light problem found with the original TIRS design [2]. As with all Landsat image data, careful efforts were made both pre-flight [3] and on-orbit [4] to fully characterize and calibrate the TIRS-2 instrument so that the final image products were as accurate as possible. SI-traceable calibration functions were derived from pre-flight spectral and radiometric test data to convert raw detector output into at-aperture radiance units for use in the U.S. Geological Survey Landsat Level 1 product generation system. Additionally, performance metrics for noise, stability, uniformity, and accuracy were calculated from test datasets and compared to requirements. Equivalent datasets were acquired during on-orbit commissioning using the onboard calibration sources to adjust the calibration functions for actual in-flight operating conditions [4]. With updated calibration coefficients, users can expect data products that have met or exceeded requirements: Image noise (NEdT) is less than 100 mK; Radiometric instability is less than 0.1% over an orbit; Stray light effects are less than 1% maximum (more than a 10x improvement over the Landsat 8 TIRS instrument); and absolute radiometric accuracy is approximately 1.4% (over source temperatures of 260 to 330 K).

As TIRS-2 is expected to continue the Landsat thermal band legacy for the next decade or more, efforts are already underway to develop the next generation thermal sensor design. Engineers at NASA Goddard Space Flight Center have recently flight tested the Compact Thermal Imager (CTI) [5] which demonstrates an improved detector design utilizing strained-layer superlattice (SLS) technology providing higher quantum efficiencies than the quantum well infrared photometer (QWIP) technology utilized by the TIRS instruments. Additionally, plans are being formulated for the next generation Landsat series, known as Landsat-Next [6]. The instrument design for this system will increase the number of thermal infrared bands to five, providing increased surface temperature and emissivity accuracy. These potential future improvements in thermal band measurements will ensure the continuing legacy of the Landsat thermal infrared collection well into the future.

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Parallel Session K3: Noble Metal Thermocouples

Calibration and Testing

Effect of high temperature on the inhomogeneity of Pt-Rh noble metal thermocouple
Ferdouse Jahan and Mark Ballico (National Measurement Institute of Australia, Australia)

In-situ traceability to the ITS-90 using integrated self validating thermocouples - trials of the INSEVA thermocouple
Declan JL Tucker (National Physical Laboratory, United Kingdom (Great Britain)); Jonathan Pearce (NPL, United Kingdom (Great Britain)); Trevor Ford and Phillip Williams (CCPI Europe Ltd, United Kingdom (Great Britain)); Paul Rau (WSH - Werkzeugstahl-Härterei GmbH, United Kingdom (Great Britain)); Peter Cowley (CCPI Europe Ltd, United Kingdom (Great Britain))

The High-Temperature Irradiation-Resistant Thermocouple Manufacturability, Calibration, and Use
Richard Skifton (Idaho National Laboratory, USA); Scott Riley and Brian Jaques (Boise State University, USA)

Examining Failure Modes of in-service W-Re Thermocouples
Todd Leonhardt (Rhenium Alloys Inc., USA); Herb Dwyer (Nanmac Corp, USA)

Effect of high temperature on the inhomogeneity of Pt-Rh noble metal thermocouple.

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Platinum (Pt) and alloys of platinum and rhodium (Rh) thermocouples, known as type R and type S, are widely used for high temperature measurement up to 1600 °C. The typical calibration uncertainty ranges from 0.1 °C (eg. from NMIs) to 0.5 °C. For the highest level calibrations, three sources of uncertainty dominate: inhomogeneity, reversible hysteresis, and drift. At temperatures up to 1100 °C it is well known that the inhomogeneity of these thermocouples is the major source of calibration uncertainty, as reversible hysteresis and drift effects can be quite small. However, at temperatures above 1100 °C, these effects become much larger. Although many techniques have been developed to calibrate Pt-Rh thermocouple at high temperatures: melt-wires (eg Au, Pd), pure-metal fixed points (eg Pd in ceramic crucibles), and metal-carbide fixed points (eg Co-C or Pd-C in carbon crucibles), there is little information on these effects at high temperature. This work shows that the inhomogeneity of the thermocouples, and hence the uncertainty of calibration, is drastically affected when used at high temperatures (>1100 °C).

In this paper we present preliminary measurements of the inhomogeneity of 8 thermocouples. These thermocouples were recently used in an APMP supplementary comparison APMP.T-S16. This comparison is on the calibration of type R thermocouples at Cu, Co-C and Pd points (we note that the de-identified inhomogeneity data presented here is the pilots alone and does not affect the comparison). The inhomogeneity is measured using NMIA's high-precision and resolution scanning oil bath at a temperature of 200 °C. The thermocouples were calibrated using a wide range of furnace and fixed-point cell designs, enabling a preliminary assessment of the effect of calibration techniques on the stability of the thermocouples. Although comprehensive steps were used for all calibration systems to reduce any contamination effects, significant differences in both reversible and irreversible changes in the thermoelectric signature of the thermocouples are apparent as shown in Fig. 1. In the best cases, we observe that there is always a significant increase in inhomogeneity, from ±0.009% to ±0.020%, after calibration to 1550 °C. However in some thermocouples, we observe an increase of inhomogeneity of ±0.07% to ±0.10%, which appears to be largely irreversible and not improved by insulated limited annealing at 1100 °C. The effect of immersion length on the measured inhomogeneity is also apparent. We show that drift and inhomogeneity changes are significantly greater when used in neutral atmosphere as compared to oxidizing atmospheres. A more detailed analysis of the factors influencing type-R thermocouples will be provided once the comparison report is completed.

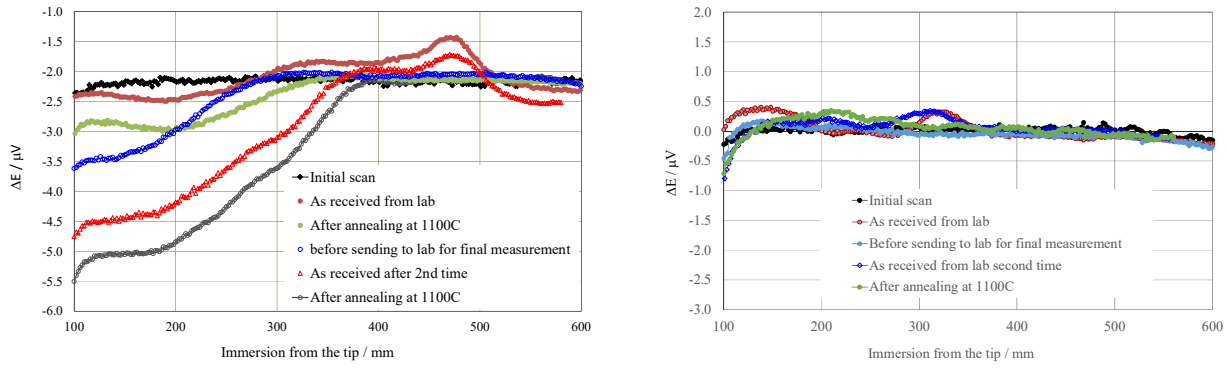

Fig 1. Typical inhomogeneity scans of two type R thermocouples in different stages of the comparison. Each thermocouple had been exposed to different calibration procedures.

In-situ traceability to the ITS-90 using integrated self validating thermocouples – trials of the INSEVA thermocouple

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Thermocouples are one of the most commonly used temperature sensors in industry, but over time they suffer from calibration drift due to exposure to a variety of factors such as high temperatures, thermal cycling, chemical attack, and transmutation. As a result, thermocouples can suffer from unknown temperature errors, causing higher energy usage, increased product wastage due to incorrect control temperatures, and possible safety issues [1].

The integrated self-validating thermocouple (INSEVA) device was originally developed as part of the European Metrology Programme for Innovation and Research (EMPIR) project "Enhancing process efficiency through improved temperature measurement", EMPRESS [2]. The device is a standard alumina sheathed noble metal thermocouple with a miniaturized metal fixed-point cell in close proximity to the measurement junction. When the thermocouple is heated above the melting temperature of the fixed-point ingot, the melting curve is detected and used to validate the thermocouple's temperature-electromotive force (emf) relationship at the fixed-point temperature, in the same way that full sized metal fixed-point cells are used to calibrate thermocouples in calibration laboratories.

The aim of this investigation was to assess the performance of the INSEVA thermocouples in a real industrial heat treatment process, building on previous work [3]. We report on the industrial tests performed using five Type S INSEVA thermocouples in a vacuum furnace, whilst heat treatment processes were being carried out. Of the five INSEVA thermocouple fixed-point cells tested, two contained silver, and the other three contained gold, copper, and an iron-carbon eutectic alloy respectively. Regular Type S thermocouples were also measured alongside the INSEVA thermocouples.

In this paper, we report the results of tests when thermally cycling the thermocouples regularly up to 1000 °C, and occasionally up to 1200 °C. Additionally, the thermocouple robustness was assessed when the furnace was routinely quenched with nitrogen at an ambient pressure of up to 10 bar. We also discuss the mechanism of extracting the melting curve values from the data, and the steps required to fully automate the process of thermocouple self-validation for end users.

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The High-Temperature Irradiation-Resistant Thermocouple Manufacturability, Calibration, and Use

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The Idaho National Laboratory's Measurement Science group has advanced the capabilities of the nuclear grade: High-Temperature Irradiation-Resistant thermocouples (HTIR-TC) Ref. [1] to measure real time temperatures of fuels and the general in-core environment. The HTIR-TC is comprised of a mineral insulated, metal sheathed (MIMS) cabling with niobium and molybdenum thermoelement junction and niobium outer sheath. The refractory metals Nb and Mo were utilized for their extreme high melting temperature (2,469°C and 2,623°C, respectively) and relatively low neutron absorption cross section (1.48 barns and 2.48 barns, respectively)—in contrast to the other refractory metals.

The Nb/Mo TC has been studied at the INL since the mid to late 1980's (Ref. [2]). However, over the last 10-15 years the INL has advanced the HTIR-TC to be directly applied to fuels experiments (Ref. [1]). Advancements in HTIR-TC manufacturing, heat treatment, and calibration (Ref. [3]) have made the TC more accessible, ductile, and stable. The stability (or signal drift) has been characterized for long term use in any nuclear experiment, fuels test, or commercial plant showing the HTIR-TC can survive within a commercial plant's 18- to 24-month refueling cycle.

Both micro and macro levels of detail have been analyzed on the modes of failure of the HTIR-TC thermoelements, insulation, and outer sheath. Through scanning electron microscope (SEM) analysis the alumina insulation has been seen to disassociate at high temperatures—greater than 1290 ℃—and the disassociated aluminum atoms can intercalate specifically into the niobium thermoelement. The solid-state diffusion of aluminum into the thermoelement leads to rapid decalibration of the TC. One way to avoid this during application is to "pre-damage" the TC by heat treating the length of the cable. The heat treatment temperature is to be in excess of the application temperature by at least 100℃. Neutron bombardment in the reactor environment further convolutes the signal by transmuting the Nb thermoelement into Mo. Finally, it has been found that repeated, large, temperature transients (>10 K/s) can cause guillotine fractures of the TC cable leading to complete failure of the TC.

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Examining Failure Modes of in-service W-Re Thermocouples

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During the lab testing and lab examination of various combination of material systems used in thermocouples, over the range of 400C to 2315C (normally a Type C) under elevated temperatures and controlled environments, we wished to further examine actual thermocouples that were used in similar applications. We wanted to see how these material systems worked in furnace applications and why they failed.

Some questions we were trying to answer included:

1. Were they failures of material combinations?
2. Were they failures due to installation?
3. Were they failures due to environments that were not anticipated in the original specifications and designs?
4. Was the location of the thermocouple in the furnace a contributing factor?
5. Were they to close to the graphite heaters?
6. Did they use the wrong gas?

We had access to failed thermocouples submitted by users to our lab, requesting that we determine the causes of failure. These analyses were performed, using the techniques outlined in our paper, and results of the examination were then supplied to the user with recommendations.

In summary, while the material combinations contributed to a high (better than 90% failure), some handling and install issues were also identified.

Based on these tests and examinations, a general recommendation is to dig deeper into all the parameters of your system; better control installation techniques; work with the furnace manufacturer to better locate the thermocouple for your specific Application.

By implementing these cost-effective techniques and design considerations, you will extend the life of the thermocouples, have lower material rejects and achieve improved sintering and firing profiles. These will also lower your total cost of ownership and reduce costly downtime.

Parallel Session K4: Bio-medical Thermometry

Improving body temperature measurement on a global basis
Graham Machin (National Physical Laboratory, United Kingdom (Great Britain)); Xiaofeng Lu (National Institute of Metrology, China & NIM, China); Maria-Jose Martin (Centro Espanol de Metrologia, Spain); Igor Pusnik (University of Ljubljana, Faculty of Electrical Engineering, Slovenia); Li Wang (National Metrology Centre, ASTAR, Singapore)

Single-shot performance mapping of human febrile temperature screening equipment using a flat heat-pipe with traceable laser-engraved facial expression
Eric W. M. van der Ham (National Measurement Institute Australia, Australia)

Evaluation of Forehead Infrared Radiation Thermometers (FIRTs) at Inmetro
Klaus Natorf Quelhas and Pedro Henrique Fernandes Diniz (Inmetro, Brazil); Ricardo Savio Teixeira Moretz Sohn (National Institute of Metrology Quality and Technology - Inmetro, Brazil); Mario Anselmo Pereira Neto (Inmetro, Brazil)

Calibration Stability of Data Loggers Used for Vaccine Temperature Monitoring
Michal Chojnacky, Sam Smith and Bethany A Rodman (National Institute of Standards and Technology, USA); Tobias Herman (NIST, USA)

Improving body temperature measurement on a global basis

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The Covid-19 pandemic has brought into the spotlight something that clinicians, and in particular nurses, have known for a long time, that the measurement of body temperature has become unreliable, both in health care settings but also more widely in fever screening [1, 2]. This rise in unreliable body temperature measurement coincided with the phase out of liquid-in-glass clinical thermometers and their replacement with a plethora of different approaches; especially infra-red techniques such as tympanic membrane, forehead [3, 4] and thermal imaging.

In the light of this issue the Consultative Committee of Thermometry (CCT)[1] in 2020 established a Task Group for Body Temperature Measurement (TG BTM), whose objective was to improve body temperature measurement by infra-red methods (ear, forehead, thermal imaging) [5]. This was through the following actions: 1) Lead a global comparison of calibrators for infra-red body temperature thermometers (ear/forehead/thermal imagers), 2) Collect current best practice/standards of body temperature thermal imaging in a) health services b) airport and other screening situations around the world, and develop best practice recommendations; 3) Collect current best practice of infra-red body temperature measurement and develop best practice recommendations and 4) Review standards and work with appropriate standardisation bodies (e.g. ISO/IEC) concerned with producing standards for body temperature measurement devices.

The TG BTM has made good progress, in particular; it has published definitive and short versions of guides for body temperature measurement by ear, forehead and thermal imaging [6], prepared a protocol and apparatus for a key comparison of ear and forehead thermometer calibrators and has established better engagement with standards bodies to ensure metrology considerations are taken into account in future clinical thermometer standards. Here context of poor body temperature measurement is introduced, its importance discussed, and the work of the TG overviewed.

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[1] The CCT is a Consultative Committee of the International Committee of Weights and Measures (CIPM)

Single-shot performance mapping of human febrile temperature screening equipment using a flat heat-pipe with traceable laser-engraved facial expression

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Generated with a laser-engraver the spatial variation of the surface emissivity is employed to mimic a representative thermographic image of a human face on a heat-pipe slab. By controlling the overall temperature of a heat pipe slab the reproducible facial temperature distribution on metal surface can be set to that of a febrile individual, *i.e.*, a human face with elevated skin temperature. Made portable these "reference inner-canthi" and/or the "reference-forehead" can be used to check the effectiveness of human febrile temperature screening equipment on-site within minutes.

Specific software, written in Python, was used to convert recorded thermograph pixel files to monochrome "emissivity" bitmaps for engraving. Each thermograph pixel was converted into 10 x 10 sub-pixels to scale the overall thermograph pixel to an effective emissivity between non-ablated to fully-ablated anodized aluminum. With the spatial resolution of roughly 9 µm of the laser engraver a typical radiance temperature pixel set of 0.9 mm square was created. The conversion model uses the heat-pipe set temperature, ambient temperature and the range of emissivities available with one or ablated 100 sub-pixels to calculate what engraving "emissivity" realizes the thermograph pixel as seen by an imager. Using empirical data from various anodized aluminum samples with different ablation density levels a direct relationship of sub-pixel engraving to radiance temperature was established. Typical a dynamic range of 3.5 °C was obtained, enough to permanently profile a human thermogram around the eyes, forehead and nose on anodized aluminum.

In this paper the approach is demonstrated where a representative inner-canthi thermogram from an ISO/IEC 80601-2-59 compliant screening thermograph is transposed onto a 250 mm x 80 mm aluminum heat pipe slab which is actively held at constant temperature. Directly next to the facial expression a 40 mm x 40 mm area is engraved with matching emissivity to the engraved inner-canthi region. This large feature is used to relax size-of source effects and measure the inner-canthi equivalent temperature with a calibrated hand-held infrared single spot radiation thermometer. As the measured radiance temperature is dependent on the reflected ambient radiation the slab can also be fine-tuned to actual ambient conditions, again using the rectangular reference area. The reference facial temperature distribution can be set to febrile temperatures to verify correct operation of walk-through screening booths or real-time performance comparison of different thermal imager systems in public temperature screening application.

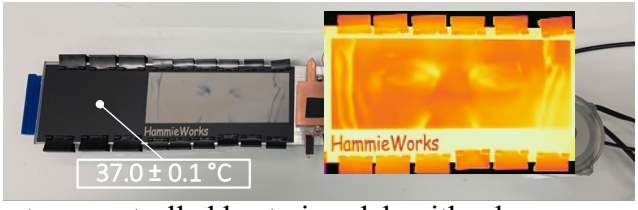

Fig. 1. A portable temperature-controlled heat pipe slab with a laser engraved facial thermograph image.

Evaluation of Forehead Infrared Radiation Thermometers (FIRTs) at Inmetro

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One of the consequences of the Covid-19 pandemic was the sudden and rapid increase in the use of forehead infrared radiation thermometers (FIRTs) for mass fever screening, in special during the first wave of the disease in 2020-2021. However, there was no evidence of the reliability of the use of FIRTs for measuring core body temperature in the literature, even after several studies have been performed.

Before being clinical thermometers, FIRTs are infrared radiation thermometers (IRTs) and so, in this work, they were evaluated as such. If they are not reliable as IRTs, the same can be said about their reliability as clinical thermometers, but the inverse in not necessarily true. Therefore, we evaluated 18 FIRTs of 10 different models under a metrological point of view. They were calibrated in both *direct mode* (when there is no corrections applied to the readings) and *adjusted mode* (when corrections are applied to relate the skin temperature to the core body temperature) against a commercial flat plate infrared calibrator and a reference blackbody cavity, especially designed and built for this study (see Fig. 1), to be operated inside a stirred water bath with an uncertainty of the order of 18 mK.

The results showed that only 50% of the FIRTs presented errors lower than 0.3 °C in *direct mode*, as required by the ISO/IEC 8061-2-56:2017 standard [1]. For the tests in *adjusted mode*, since there is no standard for skin surface temperature, the FIRTs were compared to each other. The degree of agreement between the FIRTs in *adjusted mode* was much worse, specially at higher temperatures (see Fig. 2), demonstrating that the FIRTs available in the market are in general not reliable as clinical thermometers. The results also demonstrated a good agreement between the the measurements performed with the flat plate calibrator and the blackbody cavity, although the uncertainties resulting from the calibrations with the former were too high to allow a proper assessment of FIRTs' accuracy.

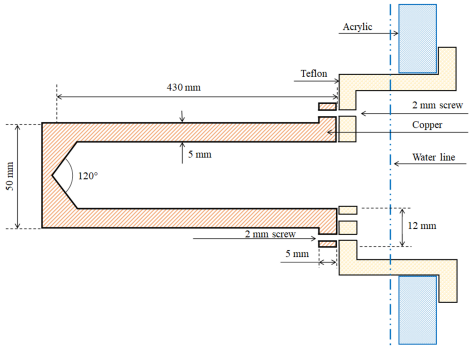

Fig. 1. Reference blackbody cavity design.

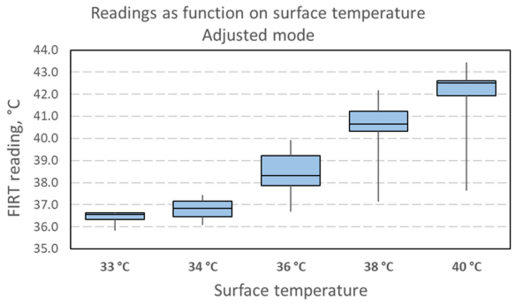

Fig. 2. Boxplot illustrating the dispersion in *adjusted mode*.

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Calibration Stability of Data Loggers Used for Vaccine Temperature Monitoring

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To ensure vaccine efficacy, it is essential to continuously monitor the temperature of the vaccines during distribution and storage. If excursions go unnoticed, exposure to improper storage temperatures can weaken the effectiveness of vaccines, endangering both products and patients. To keep a running log of the temperature history of vaccine storage, U.S. vaccine providers frequently use digital temperature data loggers. It is unknown, however, whether particular handling or use circumstances influence measurement drift in data loggers. Here, we demonstrate how common usage scenarios experienced at the level of vaccine providers have little to no impact on the calibration status of data loggers. In a two-year period between 2019 and 2021, forty commercial digital data logger devices representing eight distinct models that were marketed for use in vaccine temperature monitoring were assessed. The instruments were calibrated upon delivery, put through tests intended to mimic typical use scenarios, and then periodically recalibrated to assess potential measurement drift. Daily use in vaccine refrigerators and freezers, battery replacements, local transport, cross-country shipment, and long-term storage were all scenarios that were simulated. Extremely infrequent out-of-tolerance calibration measurements were found, and the few failures we did find didn't seem to be connected to any of the use trials conducted over the course of the two-year study period. When combined with concurrent manufacturer-supplied device stability data and/or intermediate data logger verification checks carried out in the field, these findings support extending data logger recalibration intervals.

Poster Session 2: Radiation Thermometry, Humidity and Trace Moisture Measurements

Thermometer Metrology of Weather Stations
Wyatt Miller (National Institute of Standards and Technology, USA)

Determination of Water Vapor Enhancement Factors in Carbon Dioxide
Patrick Raab and Helmut Mitter (BEV EplusE, Austria)

A dew-point hygrometer based on tunable diode laser absorption spectroscopy
Hisashi Abe (National Metrology Institute of Japan, Japan)

Uncertainty analysis of NMIJ high humidity standard revisited
Naoya Ishiwata and Hisashi Abe (National Metrology Institute of Japan, Japan)

Development of a trace-moisture analyzer based on a rapid-scan cavity ring-down spectroscopy
Minami Amano (National Metrology Institute of Japan, Japan); Norihiko Nishizawa and Hideki Tomita (Nagoya University, Japan); Hisashi Abe (National Metrology Institute of Japan, Japan)

A novel Reference Blackbody for Tympanic Thermometer Calibrations based on an Ammonia-Heatpipe Blackbody with a Temperature Controlled Aperture
Ingmar Mueller (Physikalisch-Technische Bundesanstalt (PTB), Germany); Christian Monte (Physikalisch-Technische Bundesanstalt, Germany)

Design and Characteristic of Water Heat Pipe Blackbody Source
Shuai Huang and Ang Huang (National Institute of Metrology, China); Chengyu Bai (Natioanl Institute of Metrology, China); Jing-hui Wang (National Institute of Metrology (NIM) & Tsinghua University, China)

Size-of-source effect (SSE) in radiation thermometers: Correlations evaluation and uncertainty estimation
Gonzalo Andreu and Rocío del Pilar Napan Maldonado (INTI, Argentina); Javier García Skabar (INTI - Instituto Nacional de Tecnologia Industrial, Argentina)

Self-validating reference ice-point blackbody for IR radiation thermometers using 3D printed elements
Eric W. M. van der Ham (National Measurement Institute Australia, Australia)

Realizing Fe-C, Pd-C, Ru-C, and WC-C eutectic fixed-points at UME
Humbet Nasibli (TUBITAK-UME National Metrology Institute, Turkey); Mehtap Can, Can Gözönünde and Ömer Faruk Kadı (TÜBİTAK UME, Turkey); Mücahit Korkmaz (TUBITAK UME, Turkey)

Thermodynamic temperature measurement of an Al FP used for radiation thermometry
Maria-Jose Martin-Hernandez and Jose Manuel Mantilla (Centro Español de Metrologia, Spain)

Application of Computational Fluid Dynamics for the Analysis of the Furnace Effect in the Determination of the Temperature of High Temperature Fixed Points
Pablo Castro (Universidad de Cantabria, Spain); Graham Machin (National Physical Laboratory, United Kingdom (Great Britain))

Thermal band observations of the May 2022 Total Lunar Eclipse by the Landsat Thermal Infrared Sensor (TIRS)
Matthew Montanaro (NASA Goddard Space Flight Center & Rochester Institute of Technology, USA); Dennis Reuter (NASA Goddard Space Flight Center, USA); Allen Lunsford (NASA Goddard Space Flight Center & American University, USA)

NIST Report of Weather Station Liquid-in-Glass Thermometer Metrology

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In 2011, the National Institute for Standards and Technology [NIST] Thermodynamic Metrology Group [TMG] initiated a study of historical weather temperature observations in support of the National Oceanographic and Atmospheric Administration's [NOAA] National Climate Data Center [NCDC], (now part of the National Center for Environmental Information [NCEI]), which maintains comprehensive oceanic, atmospheric, and geophysical data. Historical weather observations provide critical baseline data for climate change predictions and analysis of earth surface temperature trends. However, the uncertainty of historical weather observation data has not been thoroughly documented or explored. A comprehensive understanding of the contributions to and the magnitude of this measurement uncertainty is needed to discern the implications of recent climatological predictions. In this study, NIST replicated historical weather observation techniques alongside a modernized, metrologically-sound data collection process. This process was designed to reduce measurement uncertainty, while adhering to historical environmental conditions and instrumentation where possible, to ensure optimal comparability. Our results show that the uncertainty $k = 2$ for Liquid-in-Glass [LIG] thermometers used in weather stations is on the order of 1.09 °C to 1.68 °C for mercury LIGs and 1.56 °C to 2.54 °C for organic LIGs over the range of 0 °C to 30 °C.

Figure 1. NIST Weather Box 1, Stevenson Shelter (shown with access door open).

Determination of Water Vapor Enhancement Factors in Carbon Dioxide

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Accurate dew point monitoring in carbon dioxide (CO_2) - for example in CO_2 recycling systems - gained importance in industry in the last years. The monitoring is necessary to prevent condensation which would lead to corrosion and thus must be avoided in such cases. Furthermore, CO_2 may replace the commonly used sulfur hexafluoride (SF_6) in high-voltage switchgears. CO_2 or CO_2-rich gases would be highly favorable in this case, as SF_6 exhibits a global warming potential 20 000 times larger than CO_2. Dew- and frost point monitoring in high voltage switchgears is undoubtedly necessary to prevent electric shortcuts.

To determine the dew point in CO_2 accurately, the fundamental thermodynamic properties of the water carbon dioxide mixture must be known. These properties are usually expressed in the form of so-called water vapor enhancement factors which are varying on the used carrier gas. Enhancement factors in CO_2 were presented by C. Meyer and A. Harvey from NIST [1] in the temperature range from 10 °C to 80 °C at pressures between 0.5 MPa and 5 MPa. Here enhancements factors are determined fundamentally by use of a gravimetric hygrometer and directly measuring the water mole fraction in the carrier gas. At lower pressures and negative °C - temperatures currently no data exists.

Instead of a gravimetrical hygrometer, a two-pressure two-temperature primary humidity generator is used in combination with a dew point mirror to monitor the dew point at atmospheric pressure, while the pressure in the generator is varied at fixed temperatures. The same generator is also used as reference in the Designated Institute for Humidity in Austria. From the generator parameters and the measured dew point temperatures relations of enhancement factors can be calculated directly as a function of applied pressure. From these pressure dependencies an enhancement factor is then determined.

We recorded measurement data above water saturation at isotherms between 2 °C and 90 °C in a pressure range from 0.1 MPa to 0.95 MPa. Additionally, we also measured these parameters and dew/frost point temperatures above ice saturation between - 40 °C and -10 °C from 0.1 MPa up to physically reasonable pressures (without CO_2 phase changes). This approach allows us to reliably determine enhancement factors, which are in very good agreement with the data presented in the work [1] considering the stated uncertainties. Enhancement factors in the carrier gas CO_2 are indispensable in accurate dew/frost point measurements. A functional description for saturation above ice and water is calculated from the current experimental data under consideration of the NIST data.

References

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A dew-point hygrometer based on tunable diode laser absorption spectroscopy

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The demand for hygrometers usable in a wide range with fast response time has been increasing in various industrial fields. Many different types of humidity sensors, such as capacitive humidity sensors, quartz crystal microbalance sensors, electrolytic moisture sensors, and chilled mirror hygrometers are commonly used to measure humidity in a wide dynamic range. However, these sensors tend to show slow response in the low humidity range (lower than a frost point of –50 °C). This would be a serious problem in some manufacturing processes, such as lithium-ion battery where humidity control at the low level is critical for the yield and product performance. The reason for the slow response is because those sensors detect moisture in the hygroscopic materials or on the surface of a mirror that are in equilibrium with ambient water vapor, and it takes a long time to attain the equilibrium state in the low humidity range.

To address this issue, we developed a dew-point hygrometer based on tunable diode laser absorption spectroscopy (TDLAS) usable for the frost-point range of –70 °C to –20 °C. In contrast to the equilibrium-based methods stated above, spectroscopic methods can directly detect water molecules in gas phase and therefore show faster response time. The performance of the TDLAS-based hygrometer was evaluated in terms of measurement accuracy, time response, and long-term stability using a primary humidity standard traceable to the International System of Units (SI) at the National Metrology Institute of Japan (NMIJ). The details of the analysis will be presented.

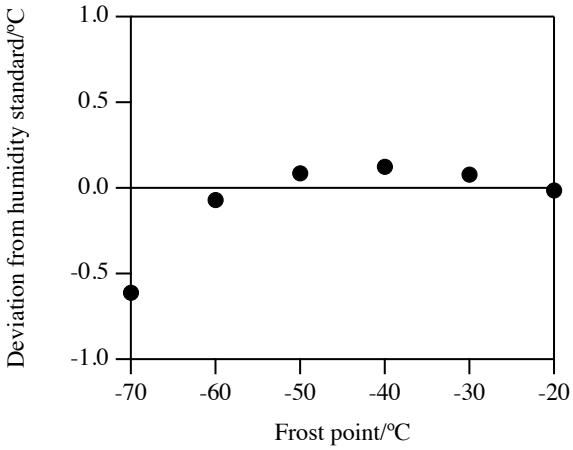

Fig. 1. Comparison with primary humidity standard.

Uncertainty analysis of NMIJ high humidity standard revisited

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In recent years, the accurate measurement of humidity has become necessary in various applications such as climate monitoring and automobile manufacturing. To meet this need requires primary humidity standards to accurately calibrate hygrometers used in such applications in a manner traceable to the International System of Units (SI). The National Metrology Institute of Japan (NMIJ) developed a two-pressure high humidity generator to establish an SI-traceable primary humidity standard in the dew-point range of -10 °C to 95 °C almost 20 years ago, and the standard uncertainty was in the range of 15 mK to 43 mK. At that time, some uncertainty components of measuring instruments used in the generator were overestimated because of the lack of the experimental data. However, during the past 20 years, the massive amount of the experimental data have been accumulated. In addition, improvement of the generator and optimization of the operational parameters have also been made. These suggest the possibility of reducing the uncertainty.

In this study, we revisited the uncertainty analysis to investigate the possibility of reducing the uncertainty and to understand the dominant uncertainty components in the current system of the humidity standard. Figure 1 shows standard uncertainty of reproducibility of the pressure gauge for saturator-pressure measurement $u_{\mathrm{PG\text{-}repro}}(P_1)$, which was one of the dominant uncertainty components whose values could be decreased from the analysis of the experimental data. This uncertainty became less than 1/100 of that in the previous analysis, which was estimated using specifications of the instrument. We also found that some uncertainty components became larger than that in the previous evaluation. Figure 2 summarizes the combined standard uncertainty of generated dew-points $u(T_{\mathrm{d,\,gen}})$ evaluated in this study as a function of dew-point $T_{\mathrm{d,\,gen}}$ in the range of -10 °C to 95 °C, where the black filled diamonds and the red filled circles represent the uncertainty evaluated previously and in this study, respectively The combined standard uncertainty obtained in this study was 10 mK or less, which was lower than that evaluated previously in the entire range of $T_{\mathrm{d,\,gen}}$.

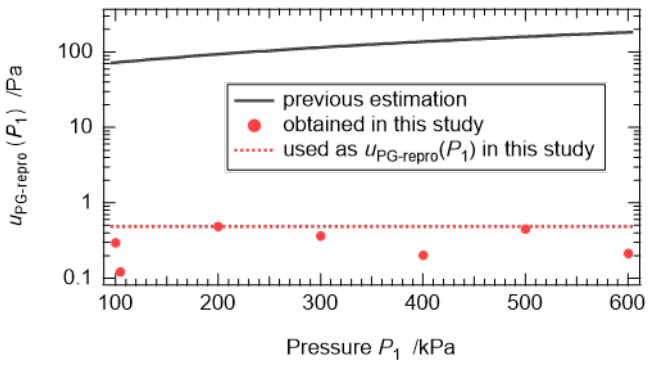

Fig. 1. Standard uncertainty of reproducibility of the pressure gauge for saturator-pressure measurement $u_{\mathrm{PG\text{-}repro}}(P_1)$ obtained in this study (red) and the previous estimation (black).

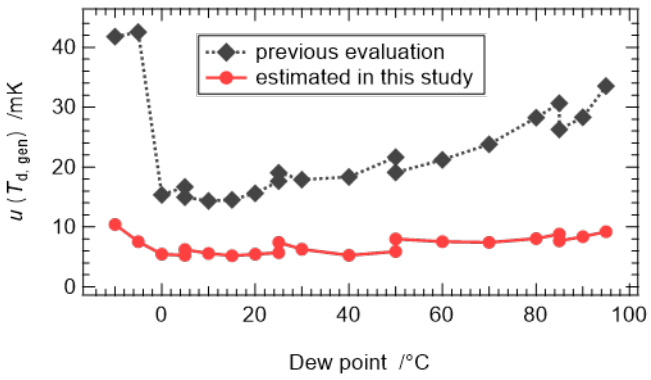

Fig. 2. Combined standard uncertainty of generated dew-points $u(T_{\mathrm{d,\,gen}})$ estimated in this study (red) and the previous evaluation (black).

Development of a trace-moisture analyzer based on a rapid-scan cavity ring-down spectroscopy

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In the manufacturing processes of semiconductor devices, trace moisture included in ultra-high-purity gases as an impurity must be controlled at 1 nmol mol^{-1} (ppb) level. Many moisture analyzers (MAs) based on various principles are developed and used to measure trace moisture in the gases. Among them, the cavity ring-down spectroscopy (CRDS) is considered as the most reliable method for the measurement of trace moisture. CRDS-based MAs use an optical cavity composed of high-reflective mirrors as a sample cell. Laser light is introduced to the cavity. Moisture concentration in the sample gas is determined from the measurement of ring-down time, which is a time constant of the decaying laser intensity while the laser travels between the mirrors. The ring down event is observed only when the frequency of the laser coincides with the resonant frequencies of the cavity. Various techniques have been developed to control the laser accurately and efficiently to the resonant frequency of the high-finesse cavity.

We have been developing a new CRDS-based MA named "rapid-scan CRDS" where the laser frequency (wavelength) is varied by sweeping its drive current rapidly [1]. The length of the cavity used in this study was 60 cm (i.e., free spectral range (FSR): 0.0083 cm^{-1}) and the reflectivity of the mirrors was approximately 99.992 %. To perform the measurement at each resonant frequency which appears every 0.0083 cm^{-1}, we need to finish turning on/off the laser, stabilizing the frequency, and recording the ring-down signal before the laser frequency reaches to the next resonant frequency. Fig.1 illustrates the absorption line of water in N_2 around 7181.2 cm^{-1}, obtained using the rapid-scan CRDS. The reference gas was supplied from our primary trace-moisture standard generator, Multi-gas Trace-moisture Generator. We optimized some parameters, such as scanning speed and timing to turn on/off the laser, to achieve ring-down time at almost all the resonant frequency in one sweep. The measurement time for the one sweep was 5 s. The standard value of the reference gas was (507.4 ± 1.6) nmol mol^{-1}. The measured value was (506.7 ± 3.9) nmol mol^{-1}, which was in good agreement with the standard value. In this presentation, the outline of the rapid-scan CRDS and its performance based on comparisons with the trace-moisture standard in N_2 will be reported.

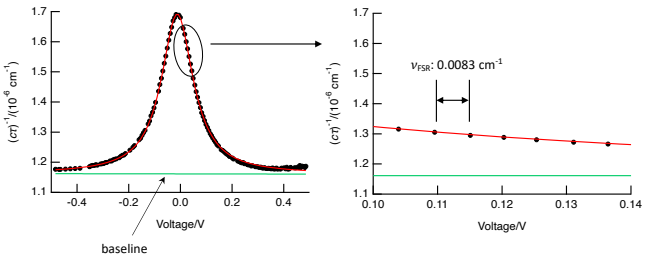

Fig.1. Absorption line of water in N_2 obtained using the rapid-scan CRDS.

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A novel Reference Blackbody for Tympanic Thermometer Calibrations based on an Ammonia-Heatpipe Blackbody with a Temperature Controlled Aperture

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During the COVID-19 pandemic, the demand for non-contact body temperature measurements grew drastically. This, in turn, resulted in a significant increase in demand for calibrations of tympanic thermometers and reference blackbodies for these devices. As result, PTB both takes part in a BIPM comparison CCT-K11 [1] and developed new calibration strategies to facilitate the calibration procedures to reduces the customer lead time and to reduce the work effort for calibrations of reference blackbodies for tympanic thermometers. To fulfill these needs, the calibration is going to be automated by means of an industrial robot and infrared radiation thermometers with similar field of view as tympanic or skin thermometer. Here, the ammonia heat pipe blackbody of PTB's new low temperature infrared calibration facility [2], extended by a tempered aperture, is presented.

When evaluating the effective emissivity of the ammonia-heatpipe blackbody of the new low temperature infrared calibration facility of PTB [2] taking into account the axial temperature distribution along the cavity and the typical field-of-view of medical non-contact thermometer, the resulting uncertainties were not compatible with the requirements of the corresponding international standards, e.g. [3]. Thus, the effective emissivity had to be increased as well as the axial temperature non-uniformity (see Fig. 2) had to be improved. Furthermore, we noticed that the thermal conductance of the material in contact with the transfer radiation thermometer has a strong influence on the calibration result when it differs too much from the blackbody under test. Thus, several adapters were manufactured to mimic the contact area of the blackbody under test. The aperture is made of copper, the outside is made of grey plastic. A heating foil is placed between the grey plastics and the copper. A calibrated pt100-thermometer measures the temperature of the aperture. This temperature is set to match the temperature of the blackbody.

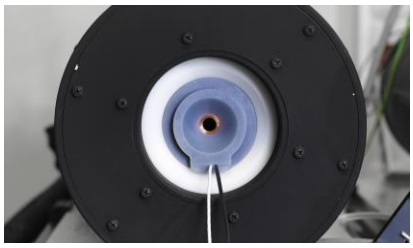

Fig. 2. Photograph of the ammonia-heatpipe equipped with the tempered aperture.

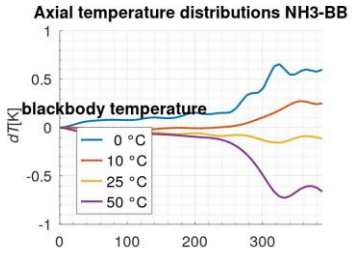

Fig. 1. Measured axial temperature profiles [2] of the ammonia-heatpipe blackbody w/o aperture.

The effective emissivity of our ammonia-heatpipe blackbody increased from 0.99674(10) to 0.99982(10). As a result, corrections of the radiation temperature are no longer necessary.

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Design and Characteristic of Water Heat Pipe Blackbody Source

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The radiation thermometers, thermal imager, thermal remote sensing instrument are widely used to measure temperature in science and industry. The blackbody sources are served as standard radiator to calibrate that instrument. The emissivity of blackbody sources have reached to 0.99-0.998 or higher in science and industry with development of research and application of the blackbody sources.

A water heat pipe blackbody (WHBB) source operate in the 50 °C to 200 °C range has been developed at National Institute of Metrology(NIM), China. It is used to establish infrared radiance temperature standard. The blackbody source includes a water heat pipe blackbody cavity, a temperature control system and a temperature measurement system. The blackbody cavity is made of Inconel 400 alloy, and the structure is designed as a cylinder-cone with 50 mm in diameter and 370 mm in depth. There are four thermometer wells in rear of black body cavity used for temperature control, alarm and measure.

The experimental characterizations of the WHBB include the temperature stability, the cavity wall axial temperature distribution and the cavity bottom radiance temperature distribution. The average normal emissivity of the cavity is better than 0.9993 and painted with Pyromark 1200 paint. The temperature stability of blackbody source is 0.05°C in 10 minutes and the temperature uniformity in the cavity bottom of blackbody source is better than 0.08°C.

Size-of-source effect (SSE) in radiation thermometers: Correlations evaluation and uncertainty estimation

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The need for rapid, non-contact body temperature measurement during the COVID-19 pandemic emergency has led to the widespread use of radiation thermometers, thermal imaging cameras, and thermal scanners in household and commercial settings as an alternative to clinical contact thermometers.

This boom in the use of this equipment, which was not limited solely to the clinical context, and the limitations and problems in the use of these non-contact temperature measurement devices require further study. It is necessary to find a simple methodology to determine if the equipment to be use can respond to the needs for which it is applied.

In radiation thermometry, the size of the source effect is known and an ever-present problem when using this type of thermometers. This is usually do not taken into account by the common user and results in measurement errors due to misuse of the instrument.

In this work, non-contact temperature measurement issues are discussed [1-2], and several SSE measurements are analysed with the goal of, evaluate the SSE source size effect on the measurements obtained from various radiation thermometers [3], estimate and analyse SSE corrections, as well as their contribution to measurement uncertainty, find a simple method of evaluating the instruments metrology quality.

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Self-validating reference ice-point blackbody for IR radiation thermometers using 3D printed elements

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Using 3D-printed elements a reference blackbody radiator (BBR) is constructed from crushed ice that enables one to verify radiation thermometers readings at 0.0 °C, *including* the associated uncertainty component for size-of-source. The latter makes this reference source very versatile as the (often dominating) size-of-source characteristics of the radiation thermometer is now incorporated in the measurement result. Using this self-validating feature makes verification of measurement results to the radiation thermometer calibration report straightforward. When created along a simple and straight-forward instruction the RADiometric Ice Point (RADIP) radiator will provide a reference source at (0.00 ± 0.08) °C with a nominal diameter of 30 mm for a period of at least 20 minutes. The cavity of the BBR is based on a crushed-ice slurry shape molded with the RADIP insert.

This 3D-printed gadget is a practical tool to make a reference/check BBR at the ice-point. A set of four STL-files was designed for straightforward duplication of this reference tool. The set comprises of a container, a cavity-molding shape, a back cover with imprinted instructions and a size-of-source cone-reflector. The author made these files and user manual available for downloading. The four items can be printed on commercial available resin and filament printers within one day, making this reference source readily available to all applications in infrared radiation thermometry.

This BBR can be employed for the checking of radiation thermometers and thermal imagers at various emissivity settings. The uncertainty of the RADIP reading by an instrument is at minimum the combined uncertainty of the RADIP itself (≤ 0.08 °C) and the size-of-source characteristic of the radiation thermometer. In most cases the latter is the dominant uncertainty which can be overestimated by using the difference in temperature reading on the RADIP with and without cone-reflector. In this paper the construction, characterization and uncertainty budget are discussed.

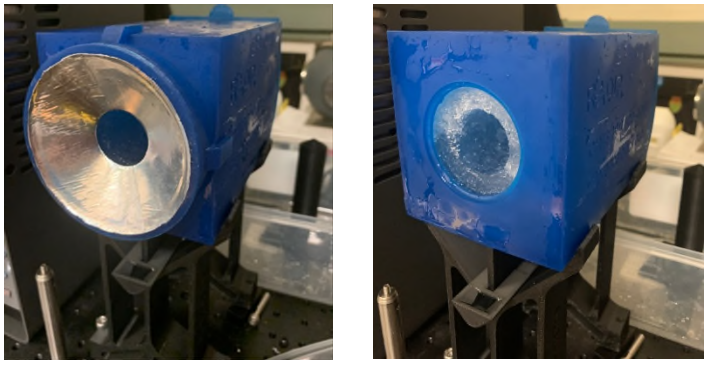

Fig. 1. The RADIP reference ice point in default configuration with well-defined diameter (left picture) using a reflective cone. When the cone is removed it reveals a controlled increase in diameter to determine dominant uncertainty (right picture).

Realizing Fe-C, Pd-C, Ru-C, and WC-C eutectic fixed-points at UME

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The *mise en pratique* of the new definition of the kelvin [1] includes relative primary radiometric thermometry methods for realizing radiation temperature scale in the high-temperature range from about 1200 K up to 3500 K. Among the approaches to applying primary radiometric thermometry, multiple fixed-point methods, based on the use of physical interpolation equations and known reference temperatures of high-temperature fixed-point blackbodies (HTFPs), are the simplest and most practical way to realize and disseminate the kelvin. These reference temperatures include the solid-liquid phase transition of one or more metal fixed points (Ag, Au, or Cu) of the current International Temperature Scale of 1990 (ITS -90) and the assigned thermodynamic temperature (and the corresponding uncertainty) of metal (carbide)-carbon eutectic and peritectic alloy-based HTFPs. Previously, in the frame of a concerted international research project, the thermodynamic melting temperatures and the associated uncertainties were determined and assigned for the Cu-point and three HTFPs, namely Co–C (1597.39 ± 0.13 K), Pt–C (2011.43 ± 0.18 K) and Re–C (2747.84 ±0.35 K) [2]. Currently, to minimize the overall uncertainty of the thermodynamic scale realization, in addition to the abovementioned HTFPs, a low uncertainty thermodynamic temperature assignment for new four HTFPs is among the objectives of the ongoing European joint project, "Realizing the new kelvin," (Real-K) [3].

In this work, we present the experimental activities carried out at UME in the scope of the Real-K project to determine the thermodynamic temperature of the circulating (the second loop) cells, namely Fe–C (1426 K), Pd–C (1765 K), Ru–C (2226 K), and WC–C (3020 K) eutectic fixed points. All cells were examined and investigated using the same high-temperature furnace. To minimize the furnace effects the most uniform temperature position inside the furnace is determined for each cell individually. The melting curves of the HTFPs were measured using a reference radiation thermometer. The point-of-inflection and the liquids temperatures were calculated using two different methods and then compared. The determination of the thermodynamic temperature of these cells and the derivation of the measurement uncertainty were conducted using both, the ITS-90 realization over Cu point and the thermodynamic temperature scales established by the multiple fixed-point methods (one-, two- and three-point schemes) using the Cu, Co–C, and Re–C HTFPs extrapolation/interpolation procedures. In addition, we describe the comparative study of the measurements obtained by realizing the circulating cells and UME cells.

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Thermodynamic temperature measurement of an Al FP used for radiation thermometry

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The current International Temperature Scale of 1990 (ITS-90) is the underpinning scale for temperature measurement worldwide. It defines instruments and methodologies, such as interpolation equations, for establishing a scale which is close to thermodynamic temperature, for temperatures above 0.65 K [1]. Instrumentation involved includes reference artefacts such as fixed points based on phase transitions of pure materials to calibrate the thermometers specified in [1]: standard platinum resistance thermometers (SPRTs) for temperatures from ~ 14 K up to 1235 K and monochromatic radiation thermometers above 1235 K.

The temperatures assigned to the fixed points on the ITS-90 were based on measurements made using the best determinations of thermodynamic temperature prior to 1990. Subsequent measurements have highlighted small departures of the ITS-90 from thermodynamic temperature across the range from 20 K to 1235 K [2], with the uncertainty in the difference being especially large above the Zn point (about 693 K) and corrections are needed to the ITS-90 values to obtain thermodynamic temperature.

This paper describes the assignment of the thermodynamic temperature of an Al FP (933,473 K) using relative primary radiation thermometry with the aim of extending the operating range of thermodynamic radiation temperature dissemination at CEM below 1235 K.

Firstly, an Al FP has been constructed using the piston method as in [3]. The Al powder purity is 99.9995 and the aperture diameter of the BB cavity is 7 mm.

The measuring method used relies on a KE LP4 standard radiation thermometer (RT) working on 650 nm and 900 nm and a KE LP5 radiation thermometer working on 1.6 μm. The absolute spectral radiance responsivity of the KE LP4 was previously determined at 650 nm [4] and has been used to assign the thermodynamic temperature of the CEM Ag FP 1234.905 K, u (k = 1) = 40 mK.

Relative primary radiation thermometry scheme applied consists of two steps: the measurement of an Ag FP with mentioned LP4 (at 650 nm and900 nm) and LP5 (1.6 μm) and the measurement of the Al FP with LP4 (900 nm) and LP5 (1.6 μm) immediately afterwards, in order to reduced uncertainty due to the stability of the thermometers.

This method provides uncertainties in the measurement of the thermodynamic temperature of the Al FP of 45 mK, using the 1.6 μm RT, and 50 mK, for the 900 nm RT (k = 1).

The construction of the cell, the measurements performed and a detailed uncertainty calculation will be described in this paper.

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Application of the Computational Fluid Dynamics for the Analysis of the Furnace Effect in the Determination of High Temperature Fixed Points

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To traceably measure the radiant energy a non-contact thermometer or radiometer should be calibrated against reference radiation sources of known temperature. These can be variable temperature blackbodies or fixed-points whose phase transition temperature is known.

High-temperature fixed-points (HTFPs) have been intensely studied in the last two decades. Yet despite this there are still sources of poorly characterized uncertainty colloquially known as the "furnace effect". This has been attributed to different factors some examples of which are: the lack of uniformity of the furnace temperature, the thermal inertia of the furnace, the microstructure of the fixed point material, the heat dissipation through the walls of the furnace and cell, the effective emissivity of the black body cavity, the characteristics of the radiation thermometer, etc. Nevertheless, all of these are too small to explain the magnitude of the temperature drop obtained. Recent research has given evidence to show that this uncertainty is almost certainly related to the configuration of the furnace and cell considered, so it is due to a purely geometric phenomenon.

In that work [1] it was shown that the furnace effect was caused by the interaction between the thermal radiation from the hot furnace and the inside of the blackbody cavity, specifically due to the reflection of the furnace thermal radiation on the sidewall of the cavity. To demonstrate this several modifications were made to a specially designed Cu fixed-point blackbody cavity. A means of reducing the diameter of the blackbody aperture, incorporation of radiation shield disks and making circumferential grooves on the inner surface of the HTFP blackbody. These improvements reduced the furnace effect contribution to the uncertainties for the copper fixed point by around 14 mK.

The aim of this paper is to apply Computational Fluid Dynamics (CFD) to the analysis of the furnace effect to better understand its mechanism and to assess how much each mitigation strategy contributes to reducing the furnace effect. The results obtained using ANSYS©, have confirmed that the introduction of the appropriate improvements in the black body cavity design allows a reduction of the furnace effect and that the most influential factor is the reduction of the cell aperture diameter, which, incidentally, confirms that this phenomenon is mainly caused by the reflection of radiation from the cavity sidewall.

In this study, it was not possible to determine with sufficient accuracy the real magnitude of the furnace effect, mainly because of the complexity of considering the variation of the specular component of the reflectance as a function of the angle of incidence of the irradiance.

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Thermal band observations of May 2022 Total Lunar Eclipse by the Landsat Thermal Infrared Sensor (TIRS)

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The Thermal Infrared Sensor (TIRS) instruments onboard Landsat 8 and Landsat 9 provide routine thermal band measurements of the Earth for the Landsat program. Although these observatories are specifically designed for mapping the Earth's surface from their 705 km altitude orbits, they were recently utilized to image the Moon during the total lunar eclipse of May 2022. The full Moon is frequently used as a calibration target for Landsat, however the imaging of the lunar eclipse provided a unique opportunity to gather temporal thermal band data over the full lunar disc. This campaign required a large effort by the Flight operations teams to coordinate acquisitions and technical constraints on both observatories to capture the long temporal extent of the eclipse. The results of this effort is a series of resolved thermal images of the Moon at discrete times as the Earth's shadow swept across the lunar surface through the start, partial, and total phases of the eclipse. This sequence of images shows an overall drop in surface temperature from approximately 370 K to 180 K in about 300 minutes as solar insolation is removed. Furthermore, the spatial distribution of different cooling rates from this unique event provide information about different material properties across the lunar surface and shows a clear distinction between mare and highland material and craters.

Parallel Session M1: Thermodynamic Temperature III

Acoustic thermodynamic calibration of capsule-type standard resistance thermometers between 10 K and 25 K
Roberto Gavioso, Dario Imbraguglio and Daniele Madonna Ripa (INRiM, Italy); Peter P. M. Steur (INRIM, Italy)

New T-T90 data from 6 K to 24.5 K by fast acoustic gas thermometry
Laurent Pitre (LNE-Cnam, France); Fernando Sparasci (Laboratoire Commun de Métrologie LNE-Cnam, France); Pascal Gambette (LNE-Cnam, France); Haiyang Zhang (The Technical Institute of Physics and Chemistry of the Chinese Academy of Sciences, China); Changzhao Pan (Shenzhen Institute for Quantum Science and Engineering, China); Bo Gao (Technical Institute of Physics and Chemistry of the Chinese Academy of Sciences, China); Mark Plimmer (LNE-Cnam, France)

Optical Refractive Index Gas Thermometry via Fixed Length Optical Cavity for in-situ Calibration of Thermometers
Jacob Ricker (National Institute of Standards and Technology, USA); Jay Hendricks (NIST, USA); Kevin O Douglass (National Institute of Standards and Technology, USA)

Acoustic thermodynamic calibration of capsule-type standard resistance thermometers between 10 K and 25 K

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In the context of the EMPIR research project "Realizing the Redefined Kelvin" (Real-K)[1] [1], we have implemented absolute acoustic gas thermometry [2] between 10 K and 25 K to evaluate the performance of this method for the direct thermodynamic calibration of capsule-type resistance thermometers on the thermodynamic temperature scale. Our implementation of acoustic thermometry is based on speed of sound measurements in He at a single pressure, chosen in the range between 65 kPa and 125 kPa, at each temperature calibration point, with non-ideality corrections relying on the accurate ab initio calculations of the thermophysical properties of He.

From the acoustic calibration of RhFe and Pt capsules, previously calibrated on ITS-90, we determine ($T-T_{90}$) differences between the thermodynamic temperature T and its approximation T_{90} by the International Temperature Scale of 1990 (ITS-90), finding them in remarkable agreement with the 2022 consensus estimate [3] of these differences within the small combined uncertainties.

We discuss the advantages of acoustic thermodynamic calibration compared to ITS-90 calibration both in terms of achievable uncertainty and practicality of use.

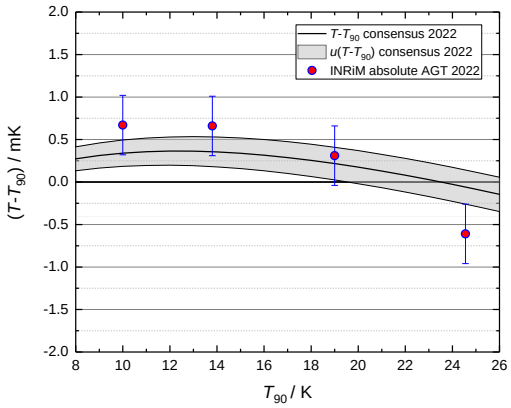

Fig. 1 Differences ($T-T_{90}$) determined using absolute acoustic gas thermometry between 10 K and 25 K.

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New $T–T_{90}$ data from 6 K to 24.5 K by fast acoustic gas thermometry

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Acoustic gas thermometry (AGT) is a primary temperature measurement technique that exploits the relationship between the speed of sound in an ideal gas and the thermodynamic temperature of the gas. AGT can be either absolute or relative. In absolute AGT, the speed of sound is determined from the resonance frequencies of a gas in an isothermal cavity. The non-ideal properties of the noble gas (usually helium or argon) are taken into account by measuring the frequencies at several pressures and then extrapolating the results to zero pressure. The extrapolation is done with the aid of an acoustic virial expansion that employs the most advanced ab initio calculations of virial coefficients. The number of pressures needed to obtain an uncertainty below 0.5 mK varies from 8 to 15 [1], depending on the temperature.

LNE-Cnam, in the European project 18SIB02 “Real-K”, has developed a "fast AGT" method to increase the speed of the AGT measurement process. This is a relative AGT method, where the temperatures are determined as a ratio with respect to a reference temperature, the latter being determined by absolute AGT on the same instrument. The reference (absolute) temperature requires obtaining measurements at multiple pressures and extrapolating them to zero pressure. All the other (relative) temperatures are measured at a single pressure that is maintained constant by a piston manometer. This provides significantly faster measurements, without any notable uncertainty degradation with respect to absolute AGT [2]. Below 25 K (Fig. 1), while determining the reference temperature requires typically 12 days, up to two relative temperatures can be measured in a single day with the fast AGT technique, saving a considerable amount of time. With this improvement, fast AGT emerges as an efficient technique for routine thermometer calibrations in thermodynamic temperature, thereby contributing to the dissemination of the new definition of the kelvin.

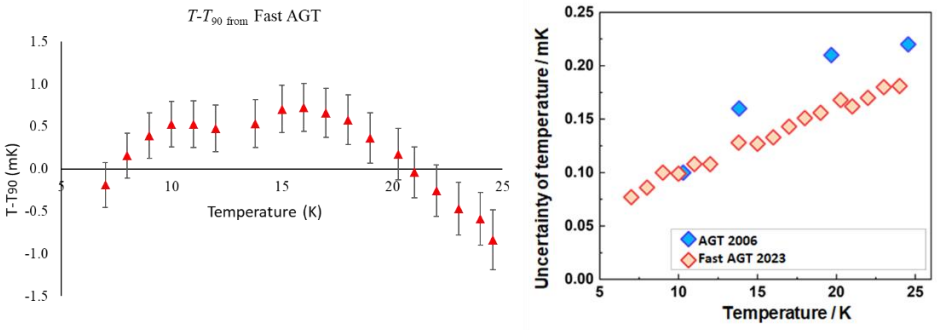

Fig. 1. Comparison of $T–T_{90}$ for the Fast AGT thin lines, standard uncertainty of $T–T_{90}$, $u(T–T_{90})$, the second graphic show u(T) for Fast AGT and AGT.

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Optical Refractive Index Gas Thermometry via Fixed Length Optical Cavity for in-situ Calibration of Thermometers

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Refractive Index Gas Thermometry (RIGT) has been established as a primary method of measuring thermodynamic temperature [1]. Typically, RIGT uses microwave frequencies to measure temperature induced refractive index changes, however optical refractive index measurements for temperature and pressure are a growing field with a variety of techniques [2]. NIST has constructed several Fixed Length Optical Cavities (FLOCs) for the purpose of measuring gas pressures by means of changes in refractive index. By using a FLOC along with an independent pressure standard, and by knowing the polarizability of the gas from theory or via precise measurements, we can determine temperature to an uncertainty of 3 mK when using nitrogen or even lower if using helium [3].

The current FLOC was developed/constructed in conjunction with MKS Instruments and is capable of operating at pressures from 1 Pa to 350 kPa. The system takes advantage of the recent advances in telecom lasers (~1550 nm) and uses mostly commercially available components. The FLOC is capable of measuring pressure to an uncertainty of less than 15 µPa/Pa, however this requires very precise temperature measurement of less than 3 mK to meet this goal. Using a piston gauge as an independent method of measuring pressure, we should be able to independently verify and/or calibrate a thermometer in-situ without removing the device from the system. The presentation will discuss the methodology and a recent calibration using this method.

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Parallel Session M2: Spectroscopic Temperature Measurement

Novel atomic and molecular systems for radiation thermometry
Stephen P Eckel (National Institute of Standards and Technology, USA); Eric Norrgard, Matthew Simons, Christopher Holloway, Kyle Beloy and Andrew Ludlow (National Institute of Standards and Technology, USA); Howard Yoon, Eric Shirley and Dazhen Gu (NIST, USA)
Invited

Temperature measurement of acetylene gas based on the double-comb absorption spectroscopy
Ang Huang (National Institute of Metrology, China); Jing-hui Wang (National Institute of Metrology (NIM) & Tsinghua University, China); Fanshan Meng and Chengqi Zhao (China University of Petroleum-Beijing, China)

Active Photonic Thermometry using Quantum Well Heterostructures and Ring Resonators
Anoma Yamsiri (University of Glasgow, United Kingdom (Great Britain)); Graham Machin (National Physical Laboratory, United Kingdom (Great Britain)); Stephen Sweeney (University of Glasgow, United Kingdom (Great Britain))

Invited

Novel atomic and molecular systems for radiation thermometry

Stephen Eckel[1], Eric Norrgard[1], Matt Simons[2], Christopher L. Holloway[2], Kyle Beloy[3], Andrew Ludlow[3], Howard Yoon[1], Dazhen Gu[2], Eric Shirley[1]

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Radiation (non-contact) thermometry currently relies on classical radiation detectors, which are typically calibrated through long traceability chains that require constant upkeep. These requirements have posed a variety of problems in fields like remote sensing, where constant recalibration of detectors is not possible. Instead, we are attempting to realize standards for radiation thermometry using either Rydberg atoms or polar molecules.

Blackbody radiation induces two effects on these systems: it shifts the transition frequency between two states and drives transitions to other internal states. The expected relative temperature precision, $T/u(T)$, can be as high as 10^5 for a sample of 10^{10} atoms or molecules. This sensitivity is shown as a function of frequency for a sample of 10^9 Rydberg atoms or molecules as a function of temperature in Fig. 1. More details are contained in Ref. [1]. Importantly, all of these systems are amenable to *a priori* calculation of the relevant observable as a function of radiative temperature, making them potentially primary sensors.

Our effort is divided into three experimental realizations. Each one sensitive to different portions of the ambient temperature blackbody spectrum. Our first experiment will realize a fountain of laser-cooled MgF molecules that probe a blackbody cavity. These molecules are sensitive to blackbody radiation around 21 THz, near the peak of the blackbody spectrum at ambient temperature. Our second experiment is devoted to measuring both internal-state of Rydberg atoms and transfer to the ionization continuum in a gas of laser-cooled Rb atoms. Using both techniques, these Rydberg-based blackbody sensors would be sensitive to frequencies between 100 GHz and 10 THz. Finally, our third experiment will use Rydberg Stark shifts to measure the temperature in an optical clock. This technique senses a weighted average of the entire blackbody spectrum and opens up new doors for optical clock miniaturization.

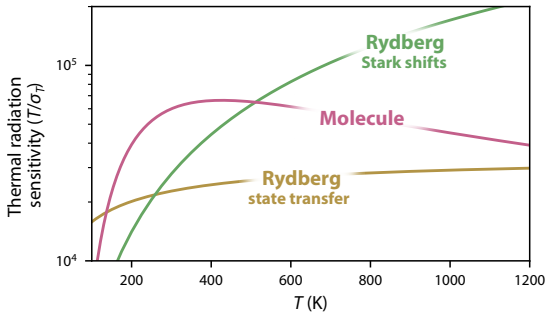

Fig. 1. Anticipated relative sensitivity, expressed in T/σ_T where σ_T is the anticipated 1 standard-deviation statistical uncertainty of a measurement with 10^9 atoms or molecules, of different blackbody radiation sensors as a function of temperature T. Figured adapted from Ref. [1].

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Temperature measurement of acetylene gas based on the double-comb absorption spectroscopy

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The dual optical comb is a new type of laser source with high-resolution comb-like spectrum. The frequency stability of the spectral comb reaches Hz level, which is suitable for high-precision spectral measurement and temperature parameter calculation. This work developed an acetylene gas absorption spectrum and temperature parameter measurement system based on narrow-laser-locked dual-combs. The laser emitted by the dual comb passed through an acetylene gas cell whose temperature varied from 25 ℃ to 150 ℃. Reference temperature was captured by a platinum resistor inserted in the cell and fed back to a temperature controller to stabilize the acetylene gas temperature within 0.1 degree. The absorbed laser was detected by a 1 GHz high-bandwidth detector, and sampled by a 200 MHz Analog to Digital Converter. The laser spectrum was recovered by using the fast Fourier transform (FFT) algorithm, and the FFT phase was utilized to suppress noise. Then the periodic data were averaged every 100 groups to obtain the absorption spectrum of acetylene gas near 1530 nm with a resolution of 200 MHz. Finally, the temperature parameters were calculated from the HITRAN database and spectral measurement model. For the acetylene gas from 25 ℃ to 150 ℃, the uncertainty of the calculated temperature less than 5%.

Active Photonic Thermometry using Quantum Well Heterostructures and Ring Resonators

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The use of photonics as a means of measuring temperature has been gaining interest over the past few years [1]. This approach typically utilises the thermally-induced change in refractive index of a waveguide or resonant structure as a means of determining the temperature. Studies initially focused on the use of optical fibers [1] and more recently there has been good progress in developing approaches using optical resonators in a silicon waveguide system for silicon photonics thermometry [1]. However, the indirect band gap of silicon means that this is intrinsically a passive approach, requiring an external laser source that substantially increases overall system size and cost. In this paper, we explore the use of the direct band gap of III-V semiconductor alloys, which are well-developed and commonly used to make laser diodes and photodetectors, to embed light sources on-chip. Here, an active photonic temperature sensor is proposed based on InGa(Al)AsP/InP alloys, as conventionally used for devices such as telecommunications lasers. The proposed structure of the sensor consists of two parts; a quantum well based active region for light emission and micro ring optical resonators for mode generation and sensing. We note here that many other resonant cavity designs are possible. The thermally induced variation of refractive indices of the optical resonators leads to a precise change in the transmission spectrum which provides an effective mechanism for measuring the temperature.

Spectroscopic ellipsometry (SE) measurements are used in a modelling process to obtain the complex refractive index dispersion of the binary compound semiconductors making-up the alloys of interest at various wavelengths from 800 nm to 1800 nm and temperatures between 298K and 573 K. A Finite Difference Time Domain (FDTD) approach is used to computationally investigate the design space for the structures and to determine the key resonant mode characteristics such as the effective refractive index, transmission spectrum, free spectral range (FSR) and the quality (Q) factor for their variation with temperature. In an initial design, an InGaAsP/InP micro ring resonator (MRR) of radius of 2.4 μm and waveguide width 0.4 μm exhibited a FSR of 38 nm and enables sufficient spacing between resonances to support single mode operation over a wide range of wavelengths. The high Q-factor of the ring structure also maintains a narrow linewidth spectrum with high intensity at the resonant wavelength thereby improving sensitivity of the resonator to temperature. Upon adding a 1550 nm Multiple Quantum Well (MQW) active region to the MRR, the simulated structure exhibited the strongest resonance at 1473 nm with a FSR around 50 nm. The thermally induced shift in the resonance of the modelled structure was found to be 7.5 nm/K. This confirms its promising approach for an active photonic thermometer, as shall be discussed.

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Parallel Session M3: Thermometry for Nuclear Environments

Temperature measurement in the core of nuclear reactors
Pattrick Calderoni (Idaho National Laboratory, USA)

Passive Temperature Sensors for Nuclear Applications
Kurt Davis, Richard Skifton and Malwina Wilding (Idaho National Laboratory, USA)

Active Temperature Sensing and Related Problems During Nuclear Reactor Operations
Richard Skifton, Joshua E Daw and Austin Fleming (Idaho National Laboratory, USA)

Phosphor thermometry for next generation nuclear waste storage
Gavin Sutton and Graham Machin (National Physical Laboratory, United Kingdom (Great Britain)); Robert Bernard and Ben Clowes (Sellafield Ltd, United Kingdom (Great Britain))

Temperature measurement in the core of nuclear reactors

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In 2012 the US Department of Energy Office of Nuclear Energy (DOE-NE) initiated the Advanced Sensors and Instrumentation (ASI) program as part of the Nuclear Energy Enabling Technologies (NEET) research to advance the state of nuclear technology, improve its competitiveness, and promote continued contribution to meet the nation's energy and environmental challenges. The objective of the ASI program is to provide reliable, cost-effective, accurate, and high-resolution measurement of the performance of existing and advanced reactor core and plant systems. Instruments are designed, fabricated, and tested in relevant and operational conditions to advance their technological readiness to a point in which they can be integrated in I&C systems without the significant cost and risk associated with development activities. This technology maturation is made possible by the deployment of developmental instrumentation in Material Test Reactors (MTRs) irradiation experiments aimed at the characterization of advanced reactor components, such as advanced fuel forms. In the near term therefore the requirements on sensor technologies are driven by the irradiation test conditions and their research objectives. Considering experiments that address both operational conditions and design basis accident cases, the requirements on temperature measurements extend from room temperature to 2000°C under extremely harsh conditions and challenging design constraints. The impact of ionizing radiation on sensor and packaging materials is the primary source of concern, leading to quick de-calibration and limited reliability.

This contribution summarizes the progress in developing nuclear instrumentation to measure temperature in the core of nuclear reactors. This work focuses on the development of melt wires fabricated with by-metallic inks as a passive monitor solution (not requiring lead wires to penetrate pressure and safety boundaries) and the development of fiber optic based sensors for real-time, multi-point and distributed measurement. Additive manufacturing (AM) based direct-write technologies have emerged as an important enabler for the fabrication of advanced passive sensors. Bismuth, bismuth/platinum, tin, tin/silver, tin/zinc, indium, and indium/silver bi-metallic nanoparticles were synthesized using the wet chemical methods. The nanoparticles were then characterized with x-ray fluorescence to evaluate the elemental composition and differential scanning to determine the melting point and mass loss of the samples. Results indicate that bi-metallic nanoparticles are a viable pathway for the fabrication of high-resolution AM melt wires, addressing the issue of large gaps existing in the melting point of pure metals at temperature of interest to irradiation experiments. Optical fiber sensing is now considered for many irradiation tests in TREAT, and through accurate selection of fiber materials (radiation hardened fibers) and interrogation techniques their performance characterization has been extended to neutron fluences that are compatible with extended testing in high flux facilities such as ATR. Temperature and radiation limits depend strongly on the sensing method and the fiber material, limiting their current applicability to less than 800°C. Several examples of the use of optical fibers for temperature measurement in irradiation experiment are presented and their results discussed.

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Passive Temperature Sensors for Nuclear Applications

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In April 2007, the Department of Energy (DOE) designated the Advanced Test Reactor (ATR) a National Scientific User Facility (NSUF) to advance US leadership in nuclear science and technology. By attracting new users from universities, laboratories, and industry, this program supports basic and applied nuclear research to help address the nation's energy security needs. In support of this program, the Idaho National Laboratory (INL) established in-house capabilities to develop, fabricate, test, and qualify new and enhanced temperature sensors for irradiation testing. This effort is continuing today through the DOE's Advanced Sensors and Instrumentation (ASI) program. Although most efforts emphasize sensors capable of providing real-time data, selected tasks have been completed to enhance passive sensors for irradiations where instrumentation leads cannot be included.

These sensors include silicon carbide (SiC) monitors, melt wires and the sublime temperature monitor. SiC monitors are available to detect peak irradiation temperatures between 200°C and 800°C in reactor locations where instrumentation leads cannot be used. SiC monitors may be evaluated using specialized equipment installed at INL's Measurement Sciences Laboratory (MSL). A melt wire inventory is also maintained at MSL. This inventory contains wires for specific use in irradiation experiments ranging in temperatures from 30°C to 1500°C. Melt wires and SiC monitors have had decades of research and application. Recent research has produced a passive monitor known as the sublime temperature monitor. This passive sensor has the capability of recording temperature gradients.

This paper will discuss passive temperature sensors currently being researched and implemented under the ASI program.

Active Temperature Sensing and Related Problems During Nuclear Reactor Operations

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Idaho National Laboratory's measurement science group has advanced nuclear-grade thermocouples Ref. [1], ultrasound thermometers Refs. [2, 3], and fiber optics Ref. [2, 4]. Each of these sensing technologies offer their own set of advantages. However, the many parameters involved in taking temperature measurements in a nuclear reactor can lead to large uncertainties and ultimately counteract any advantages gained. This summary focuses on these three different sensor technologies for measuring the real-time temperature of a nuclear reactor environment, core, and/or fuel during normal, abnormal, or test conditions. This paper further summarizes the unique problems that arise from measuring temperatures in the core, and how to mitigate large uncertainties.

Sensors located in the harsh environment of the core are directly exposed to high or extreme temperatures, neutron and gamma ray bombardment, fast temporal thermal transients, and unique chemical interactions. The temperatures can reach upward of 1800°C—and even higher in extreme cases. Neutron and gamma ray bombardment on the sensor will produce transmutation, embrittlement, and overtemperature (i.e., bias) of the sensing elements. In the case of fiber optics, it will darken the light's path as it travels within the fiber. Fast temporal thermal transients (i.e., above 10 K/s) push sensors toward becoming thermally fatigued and lead to guillotine fractures. At elevated temperatures, oxidation and solid-state diffusion of different chemicals can gradually disrupt the signal output, leading to decalibration (i.e., signal drift).

Indirectly, sensors experience flow-induced vibrations or thermal expansion of their surroundings, both of which cause a shift the sensor's known location. With sheer, spatial, and temperature gradients being commonplace in reactor cores, undesirable movement of sensors can add further uncertainty to the temperature measurements. Furthermore, the geometry of the core is limited, leading to the introduction of environmental and observational errors when the sensor is installed at the sensing location.

As can be seen, measuring temperature in a reactor core not only entails determining what sensor to use, but also how to use it and for what duration. This paper addresses both common and unique situations pertaining to measuring active temperatures in a reactor core, on the surface of fuel pins, or inside the fuel pins themselves.

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Phosphor thermometry for next generation nuclear waste storage

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Low uncertainty surface thermometry in ionizing radiation environments is essential to reliably inform thermal and corrosion models for special nuclear material (SNM) containers, as well as inform the container safety case [1]. Traditional infrared thermometers and sprung loaded thermocouples have been used in the past but suffer from large uncertainties which makes reliably measuring surface temperature drifts over large periods of time challenging. Phosphor thermometry could provide long-term, low uncertainty (< 2 °C) surface temperatures for SNM containers. This would be through a strip of thermographic phosphor, applied to the outside of the container, interrogated periodically (either *in-situ* or ex-store) by optical means. The technique has not been used in this environment before, and research was required to confirm its suitability. The objectives of this work were a) to test the applicability of a phosphor coating on SNM stainless steel containers, from 0 °C to 220 °C, b) to expose phosphor coated SNM material samples to ionizing radiation (different types and levels), representative of that encountered in the store environment and assess pre and post exposure temperature drift and c) to demonstrate instrument functionality and determine temperature measurement uncertainty in an inactive-store environment. Phosphor temperature measurements are compared with those from attached surface thermocouples. Emphasis is given during the study to achieve reproducible calibrations of a fibre-coupled instrument over the temperature range 0 °C to 220 °C, with a target measurement uncertainty of 2 °C (k = 2). The instrument design, calibration, phosphor coating recipe, ionizing radiation exposure tests, and practical field measurements are described, and a measurement uncertainty budget developed. Fig. 1 shows a) the phosphor thermometer calibration drift following exposure of coated samples to representative levels of ionizing radiation (Cf-252 – neutron) and b) comparison of phosphor and thermocouple temperature measurements on a centrally heated dummy SNM container.

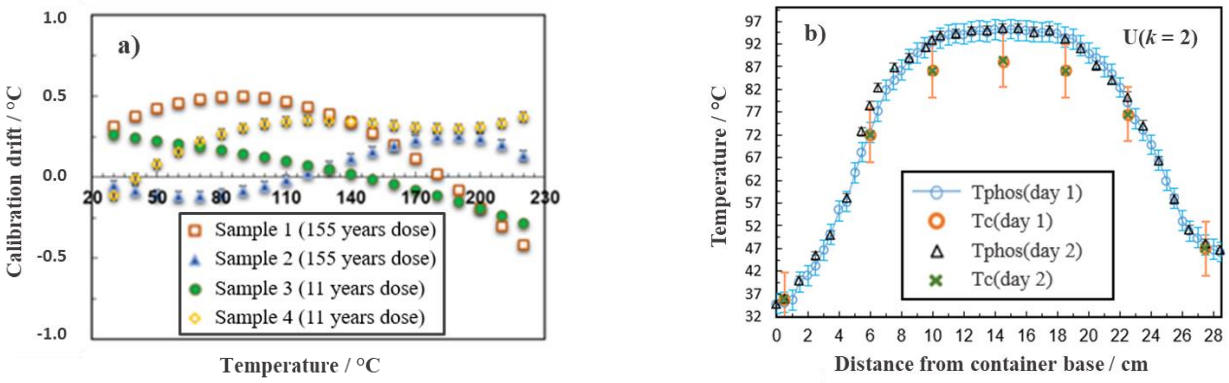

Fig 1. a) Phosphor thermometer calibration drift following exposure to ionizing radiation (Cf-252 – neutron); b) comparison of phosphor and thermocouple temperature measurements on a centrally heated dummy SNM container.

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Parallel Session M4: Traceability, Uncertainty, and Genetic Algorithms

The Purpose of Measurement Uncertainty
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Trust in measurement in a redefinition world
Andrew Todd and Patrick M.C. Rourke (National Research Council Canada, Canada); Sergey Dedyulin (National Research Council of Canada, Canada); Andrea Peruzzi (National Research Council, Canada)

Applications of Evolutionary Search Algorithms to Improve Measurement Models
Alex Cimaroli (Fluke, USA)

The Purposes of Measurement Uncertainty

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It is now more than 40 years since the BIPM announced and outlined the current harmonized approach to the expression of uncertainty in measurement [1], and 30 years since the publication of the GUM [2]. Despite the decades of use and subsequent extensive analysis of measurement uncertainty in metrological measurements, there remains a lack of clarity about the purpose of measurement uncertainty. This lack of clarity is most clearly reflected in the manner in which uncertainty is used and reported.

This paper discusses the purposes of measurement uncertainty to aid in the clarification of its usage and the way it is reported. The paper considers a single measurement example of moderate complexity, from the perspective of different users of the measurement, to identify and illustrate the purposes of measurement uncertainty. Two main purposes for uncertainty are found: one relating to decision making based on the results of measurements and employing expanded uncertainties to construct confidence intervals, and one relating to the modelling of measurement processes and employing standard uncertainties. Standard uncertainties relate to the inherent unpredictability of the measurement processes involved and must be propagated along traceability chains to deliver meaningful results. Expanded uncertainties allow interferences about the measurand to the made at the end of a traceability chain given a particular measurement result.

These two purposes explain the drift in definition of uncertainty that has occurred over 40 years, the different usage of the symbols representing uncertainty, and the way that uncertainties have come to be commonly reported and used in calibration certificates. Guidance for the usage is also provided.

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Trust in measurement in a redefinition world

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With the ramping up of efforts at many national metrology institutes to capitalize on the SI redefinition and digitalization, we would like to explore some of the fundamentals that we feel are required to continue to ensure that society and industry can trust in the measurement system. We will discuss the essential elements of this system, which include traceability and demonstrations of equivalence and proficiency. We will look specifically at each of those elements as they exist today and how we can maintain them in the context of further distributing and democratizing primary (i.e. not requiring direct calibration) sensors and the move towards digitalization. We will consider some hypothetical, but realistic, scenarios focused on temperature to hopefully cut through some of the hype around these emerging areas of metrology and how they might impact the measurement system.

In an ideal world, all sensors would directly measure the quantity desired with: accuracy suitable to application; methodology based on physical principles, infinite stability, and without other complicating factors. We know that we do not live in such a world but one of the aims of the measurement system was to help allow easier use of primary realizations and/or sensors that do not require calibration. This is a worthy aim and is already being seen. However, while this helps to push the SI traceability chain closer to the user, it only addresses one pillar (see Fig. 1) of three required to ensure that users, their customers and stakeholders, and regulators can be confident that the measurements made this way are what they say they are.

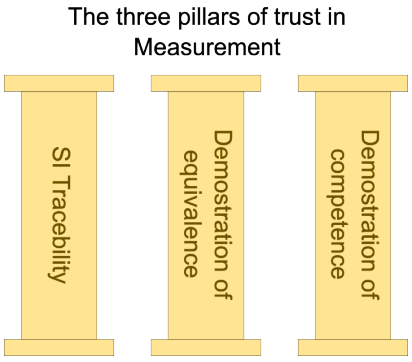

Fig. 1. The three pillars for trust in measurement

We will consider a scenario where a new primary thermometer is available and about to be put in use in a setting outside an NMI. We will consider the questions of: What is the role of the NMI? What other supporting evidence is required from the user to ensure confidence in measurement and compliance with the MRA and the Metre Convention. What role would digitalization (as outlined in the CIPM Task Group Transforming the International System of Units for a Digital World) play in this scenario?

Applications of Evolutionary Search Algorithms to Improve Measurement Models

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Many measurements are modelled by a functional relationship between input quantities and the output quantity, or measurand. To reduce errors introduced by external stimuli (e.g., internal device temperature, atmospheric pressure, ambient temperature, local gravity), measurement models can be made to incorporate the effects of these stimuli. In doing so, curve fitting of complex, large parameter models become increasingly difficult, if not impossible, using conventional curve fitting algorithms such as linear least squares regression and gradient-descent approaches.

Genetic algorithms, or evolutionary search algorithms, utilize elements of random number generation and natural selection to offer a more robust and computationally intense method of curve fitting. Given enough time, a genetic algorithm is guaranteed to find the global minimum in parameter space for even the most complex models. Genetic algorithms, applied to curve fitting, allow a measurement model to be as complex as need be to account for any number of sources of measurement error.

Two use-cases are presented: the response curve of an infrared radiation thermometer and a photonic thermometer. Steps are shown that begin with a simple model and progressively incorporate more error compensation to greatly reduce the overall measurement uncertainty. At a certain point of complexity, conventional gradient-descent-based curve fitting algorithms are not suitable, and an evolutionary search algorithm is needed to fit the radiation thermometer measurement model.

Poster Session 3: Thermocouples, Cryogenic, Photonic, Optical, Electronic, Magnetic, Instrumentation and Control

Cryogenic fixed point: effect of bushings at the triple point of argon
Javier García Skabar (INTI - Instituto Nacional de Tecnologia Industrial, Argentina); Rocío del Pilar Napan Maldonado (INTI, Argentina); Brenda Tenaglia Giunta (UNSAM, Argentina)

The Development of Cryogenic Capsule PRTs from 13K to 533K
Yu Raynee Xing and Chaoying Xing (Advanced Sensing Products, USA)

A low temperature cryostat for comparative calibration of thermometers
Aleksandra Kowal, Justyna Dobosz, Joanna Zając and Ruslan Nikonkov (Instytut Niskich Temperatur i Badań Strukturalnych PAN, Poland)

Thermometry below 1 K, a comparison of several reference sensors based on different physics principles at LNE-Cnam
Clement Tauzin (LNE-Cnam, France); Fernando Sparasci (Laboratoire Commun de Métrologie LNE-Cnam, France); Mark Plimmer and Laurent Pitre (LNE-Cnam, France)

A low-cost cryogenic temperatures measurement system
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Microwave field characteristics of NV- center of diamond for cell temperature measurement
Fan Zhenxian (Tsinghua University & National Institute of Metrology, China)

Parallel 3D temperature image reconstruction using multi-color Magnetic Particle Imaging (MPI)
Klaus Natorf Quelhas (National Institute of Standards and Technology - NIST, USA); Mark-Alexander Henn (NIST, USA); Ricardo Cordeiro Farias (UFRJ, Brazil); Weston L Tew, Jr (National Institute of Standards and Technology, USA); Solomon Woods (NIST, USA)

Practical Doppler broadening thermometry
Nicola May Agnew (University of Strathclyde & NPL, United Kingdom (Great Britain)); Erling Riis and Aidan S Arnold (University of

Strathclyde, United Kingdom (Great Britain)); Graham Machin (National Physical Laboratory, United Kingdom (Great Britain))

Progress toward driven optomechanical thermometry
Daniel S Barker and Biswarup Guha (National Institute of Standards and Technology, USA); Thomas P. Purdy (University of Pittsburgh, USA); Kartik Srinivasan, Nikolai N Klimov and Julia Scherschligt (National Institute of Standards and Technology, USA)

External sound card based practical Johnson noise thermometer
Rok Tavčar (University of Ljubljana, Slovenia); Jovan Bojkovski (MIRS/UL-FE/LMK, Slovenia); Samo Begus (University of Ljubljana, Slovenia)

Tolerance stack-up for multi-component thermocouple circuits
Richard W Phillips (Collins Aerospace, USA); Venkata Anil Kumar Mothe and Venkatasubramanian C (Collins Aerospace, India)

Drift of dual wall type N thermocouples: a study on the effect of the dual wall geometry
Michele Scervini (& ISOMIL GmbH, Germany)

Different methodologies for the assessment of thermocouple drift: a study on mineral insulated metal sheathed type N and type K thermocouples
Michele Scervini (& ISOMIL GmbH, Germany)

An investigation at high temperatures on the insulation resistance of mineral insulated metal sheathed type K thermocouples having different MgO compositions and different diameters
Michele Scervini (& ISOMIL GmbH, Germany)

Evaluation of the Realization of Rh-C Eutectic Point for the Thermocouple Calibration
Hideki Ogura and Ikuhiko Saito (National Institute of Advanced Industrial Science and Technology, Japan)

Development of an experimental device and a procedure for testing thermocouple inhomogeneities
Javier García Skabar (INTI - Instituto Nacional de Tecnologia Industrial, Argentina); Mariano Gonzalo Liste and Leandro Kornblit (INTI, Argentina); Brenda Tenaglia Giunta (UNSAM, Argentina); Rocío del Pilar Napan Maldonado (INTI, Argentina)

A Type J Thermocouple Proficiency Test
Karen Garrity (NIST, USA)

Hybrid Comparison of Co-C Eutectic Fixed-Point Cells for Thermocouple Calibration

Oijai Ongrai (National Institute of Metrology (Thailand), Thailand); Jonathan Pearce (NPL, United Kingdom (Great Britain)); Frank Edler (Physikalisch-Technische Bundesanstalt, Germany); Declan JL Tucker (National Physical Laboratory, United Kingdom (Great Britain))

Cryogenic fixed point: effect of bushings at the triple point of argon

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The metal sheath SPRT's are used in different industrial sectors because of their low cost and robustness. Calibration of them at cryogenic temperatures remains a challenge by the effects of stainless-steel stems heat conduction.

Research papers reported for the triple point of water express that the use of tubular bushings made of materials of good thermal conductivity decreases the self-heating (SH) effects and improves the thermal contact between the sensor and the cell [1-3]. Žužek et al. conducted tests at the fixed points from Zn to Hg, observing the same behavior when bushings are used [4]. At the time of writing this paper, no reported work has been found for the triple point or argon (TP-Ar) and the performance of bushings in the SH effect. Therefore, the main goal of this work was to investigate the effect of bushings on the SH of metal sheath SPRTs at the TP-Ar.

The measurements were carried out comparing metal sheath SPRT's from different end-users and hand-made bushings of copper, aluminum, and brass. In addition, the effect of SH at two immersion depths using currents of 1 mA and √2 mA was studied. Finally, the results of different test of the bushings are presented.

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The Development of Cryogenic Capsule PRTs from 13K to 533K

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Advanced Sensing Products (ASP) is a manufacturer of high temperature RTD probes with a temperature range of -196°C to 1100°C. When Minco Products, Inc. discontinued their S1059 and S9689 cryogenic capsules, ASP worked with Minco to develop and manufacture a laboratory grade secondary standard PRT and a precision RTD probe respectively using ASP's specially designed core in bore element. Both models of PRT are assembled with a standard 25.5Ω or 100Ω element with a temperature coefficient TCR >0.003925 (W(Ga) ≥1.11807). The dimensions and specifications closely match Minco's S1059 and S9689.

The laboratory grade secondary standard cryogenic capsule PRT features a custom designed wire-wound, core in bore platinum element encased in a gold plated copper case hermetically sealed with dry helium. The PRT has an operating range of 13K (-260°C) to 533K (260°C). Testing of the secondary standard PRT performed by ASP demonstrates excellent stability and repeatability when cycling from liquid nitrogen (-196°C) to ice point (0.01°C). According to data provided by Lake Shore Cryotronics, Inc., this laboratory grade sensor also has excellent stability and repeatability at 13K.

The secondary standard PRT was tested by an outside laboratory for performance in an ultra high vacuum environment. Their testing showed that at 5x10-8 Torr of pressure, there was no evidence of outgassing of any gaseous species beyond that found in the background of the vacuum chamber.

The precision RTD cryogenic capsule features a wire-wound, core in bore platinum element hermetically sealed inside a gold plated copper case. Instead of having a helium fill like the secondary standard capsule, the precision RTD capsule contains an interior substrate that closely matches the thermal expansion of platinum while also protecting the element from stress and mechanical shock. This precision RTD cryogenic capsule has an operating range of 77K (-196°C) to 533K (260°C) and features good stability and repeatability at 77K (-196°C) when cycling from liquid nitrogen (-196°C) to ice point (0.01°C).

A low temperature cryostat for comparative calibration of thermometers

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Calibration of thermometers in the range from 0 °C to 90 °C (or even to 100 °C) is not difficult because it can be performed by using a widely available liquid baths. In lower temperature, the liquid bath are not sufficient due to limited capacity of the cooling system as well as freezing of water, ethanol or oil - typical media used in such baths. Below -100 °C, thermometers must be calibrated in a special devices with a cryogenic liquids (such as liquid nitrogen) as a cooling media.

Presented device enables the calibration of thermometers by using the comparative method in the range from -196 °C to -80 °C. It is an improved cryostat which was designed and built a few years ago at the INTiBS. The modifications to the construction of the cryostat were necessary to minimize parasitic heat flow along the thermometers and temperature gradients in the comparative block. Prior the cryostat was improved, the heat flux and the temperature gradients in the comparison block were major components of total uncertainty (Table 1). However, even without modification, the cryostat designed in INTiBS showed better total uncertainty than e.g a low temperature comparator proposed by de Bruin-Barendergt et al [1].

Table. 1. Uncertainty components.

Component	Value, mK
Bridge-measurement errors	0.002
Scatter	0.004
Temperature gradient in the comparison block	0.22
Temperature stability in the comparison block	0.05
Estimated heat flux	< 0.25
Standard resistor temperature drif	< 0.001
SPRT self-heating error	0.001
Standard combined uncertainty	0.337

The measurements are carried out in the cryostat placed in the dewar filled with liquid nitrogen. Simultaneously, eight thermometers can be measured. Reference thermometer is placed in the central hole of the comparison block. The temperature of the comparative block is regulated by LakeShore 340 Temperature Controller. The pressure between the walls of the cryostat is regulated. Thus, the value of cooling power can be changed and temperature gradients in the comparison block can be minimalized. The resistance of the thermometers are measured by using thermometric bridge.

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Thermometry below 1 K, a comparison of several reference sensors based on different physics principles at LNE-Cnam

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At LNE-Cnam, we presently comparing various thermometers by using a dilution refrigerator that can reach a base temperature of 8 mK. Our set-up comprises a comparison stage equipped with 13 thermometers of different types, including resistive RuO_2 and Rh-Fe thermometers, cerium magnesium nitrate (CMN) magnetic susceptibility thermometers, superconducting transitions, and two reference helium-3 melting curve thermometers (MCT) that materialize the Provisional Low Temperature Scale of 2000 (PLTS-2000) [1]. This work aims to advance low temperature thermometry by providing a thorough comparison of different thermometer types and reference standards. We expect that future additions to our set-up, soon to be installed (a Johnson noise thermometer, a Coulomb blockade thermometer and a second sound thermometer), will provide further valuable insights.

We are currently comparing two reference MCTs thermometers with different designs, one from NIST and the other from Bell Laboratories. The two MCTs run simultaneously and are installed on the same copper plate as all the other temperature sensors. The NIST reference has a response time below 30 mK that is roughly 30% shorter, but it exhibits hysteresis and low sensitivity. The Bell Laboratories reference is smaller, has greater sensitivity, and exhibits no hysteresis. Both sensors are being used under different initial pressure filling conditions described in [1] and [2], allowing for a direct comparison with those studies.

The use of two MCTs thermometers has enabled a direct comparison and calibration of other thermometers to the reference PLTS-2000 within the temperature range of 1 K to 8 mK (Fig. 1). The CMN thermometer exhibits high sensitivity at low temperatures (<100 mK), but its sensitivity is compromised between 100 mK and 1 K, leading to a dispersion of values. However, by increasing the power in the thermometer its resolution can be improved. The two RuO_2 thermometers can measure temperatures across the full range from 8 mK to 1 K.

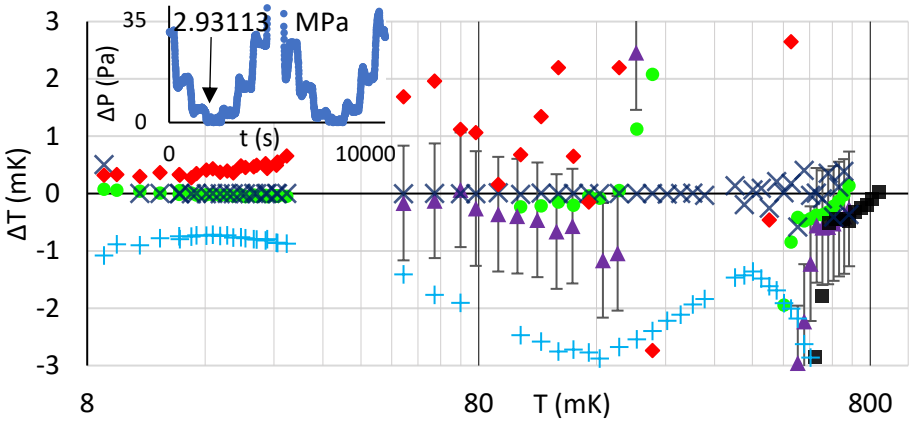

Fig. 1. Direct comparison of five different sensors to PLTS-2000 measured with the Bell Laboratories MCT. The PLTS-2000 of the NIST MCT is directly compared to the one measured from the Bell Laboratories at three different initial pressures. Keys: ■ NIST 3.58 MPa; ▲ NIST 3.48 MPa; ● NIST 3.36 MPa; ◆ Cerium Magnesium Nitrate (CMN); + RuO_2 (BlueFors calibrated); × RuO_2 (LNE-Cnam calibrated). The insert graph shows the pressure resolution measured near the minimum (315.24 mK) with the Bell Laboratories MCT.

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A low-cost cryogenic temperatures measurement system

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The need for traceability to primary standards in the cryogenic temperature range [-190 °C, 0 °C] has increased in recent years due to the rise of the biotechnology industry and other related sectors. The most recent evidence goes back to 2020, with the impact that the SARSCoV-2 virus has had in the world. It is common knowledge that the development against the clock of large-scale vaccines production, which could attenuate the severe effects of the COVID-19 disease, was an unprecedented necessity. Consequently, the demand for low temperature calibration services by accredited laboratories and some industrial sectors is constantly increasing.

In the National Institute of Industrial Technology (INTI) we have SPRT's calibration capability in range four of ITS 90 (Ar to TPW) [1-2]. However, we need to improve our dissemination capabilities at industrial level, providing us a system for calibration of PRT's by comparison for industrial use [3]. So, the main goal is to achieve a local, low-cost, with remotely monitor IoT, hand-made cryostat to disseminate the traceability of national standards to IPRT's. To obtain accurate measurements in processes performed by laboratories and related sectors at temperatures below -40 °C with an uncertainty of 0.02 °C, approximately.

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Microwave field characteristics of NV- center of diamond for cell temperature measurement

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Temperature regulation is the basic factor of chemical reaction in the living body. Living cells will produce internal temperature changes in the process of responding to environmental changes, but the temperature changes generated in this process are small and short, so it poses a challenge to temperature measurement technology. The NV color center of diamond has long coherence time, no biological toxicity, high spatial resolution, high measurement sensitivity, and can reach nanoscale temperature sensing because its fluorescence is almost unaffected by the environment, and does not display light bleaching and light scintillation. Therefore, it has become a new quantum temperature measurement technology. Since 2013, Lukin Group of the United States has used nanodiamond to obtain the fluorescence imaging map of the temperature distribution in living cells for the first time, and achieved the measurement of thermal environment at the scale of 200 nm, as shown in Ref[1]. Later, more experiments on tracking, imaging and thermal conductivity measurement in living cells have made progress. However, for the measurement of optically excited magnetic resonance, if the applied microwave power is large, it will produce obvious thermal effect. If the power is small, the thermal effect of the microwave antenna can be measured by its quality factor; The loss of the microwave antenna of the commonly used direct-conductor type is relatively large, the actual microwave power acting on the diamond will be relatively small, and the contrast of the ODMR will also be relatively small, and the contrast will affect the temperature measurement sensitivity, so the loss of the microwave antenna needs to be small. In addition, the uniformity of the microwave field will also affect the Rabi oscillation and thus the limit sensitivity, so the design of the microwave antenna is very important. However, in the process of actual measurement, we found that the results of block diamond are consistent with those of simulation, but the opposite phenomenon occurred in nanodiamond, which is also a problem to be solved later.

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Parallel 3D temperature image reconstruction using multi-color Magnetic Particle Imaging (MPI)

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Magnetic Particle Imaging (MPI) is a novel technique developed for remotely detecting magnetic nanoparticle (MNP) tracers, with great potential for biomedical imaging (as an alternative to traditional methods like MRI or CT), cell tracking, targeted drug delivery and magnetic hyperthermia. More recently, MPI has been studied as a potential method of non-contact temperature measurement, seeking to determine the temperature in the interior of optically opaque volumes, which is not possible with the current standard methods. Recent publications demonstrated the potential of the *multi-color* MPI technique for temperature imaging, with interesting results [1], while NIST is developing the *Thermal MagIC* project, which aims to establish the technologies for remote 3D temperature measurement and control.

MPI works by measuring the nonlinear magnetization response of MNPs when exposed to a combinations of static and oscillating magnetic fields, that allow scanning the desired field-of-view (FOV) at high frequencies. With enough measurements and a calibration matrix (containing the characteristic response of the MNPs to that particular MPI system), it is possible to resolve the unknown MNP 3D concentration grid by solving a linear system of equations, which is computationally expensive and time-consuming. *Multi-color* temperature-MPI (or T-MPI) adds even more complexity to this problem, by using two or more calibration matrices, one for each calibration temperature.

This work presents a simulation study of *multi-color* MPI tailored for 3D temperature measurement, and discusses how it could be implemented in a practical way. The MNP responses to oscillating magnetic fields generated by a typical MPI setup have been modelled for three different temperatures, and these models have been used to reconstruct 3D temperature maps from simulated signals (see Fig. 1). Based on the promising results obtained with GPU-accelerated parallel MPI image reconstructions [2], this work also shows a parallel implementation of the multi-color T-MPI method and that *speedups* of the order of 40x can be achieved.

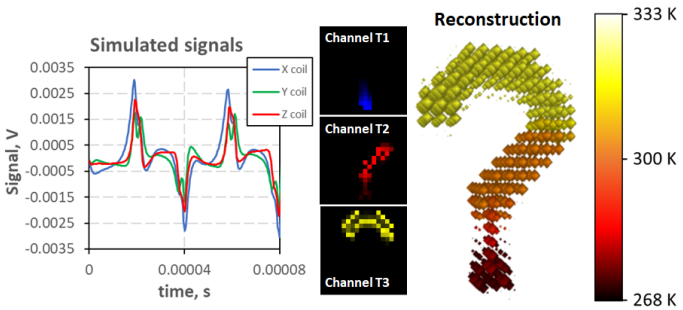

Fig. 1. 20x20x20 voxels 3D temperature image reconstruction process.

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Practical Doppler broadening thermometry

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The *mise en pratique* for the definition of the kelvin (*MeP*-K-19, [1]) has opened new possibilities for practical primary thermometry as a means of providing *in-situ* traceability for temperature. Provision of such traceability is a long-term objective for the international thermometry community as currently the overwhelming majority of thermometry approaches (resistance based thermometers and thermocouples) require periodic traceable calibration against the International Temperature Scale of 1990 (ITS-90) [2] to maintain reliable operation. One approach to providing *in-situ* temperature traceability, Johnson Noise Thermometry [3], is already well advanced, whilst a number of photonic based approaches are under active investigation [4]. Here we report our initial research to develop a compact and practical primary thermometer based on Doppler Broadening Thermometry (DBT) [5-7]. The DBT sensor uses an intrinsic property of thermalized atoms, namely, the Doppler width of a spectral line characteristic of the atoms being probed [8-10]. The DBT sensor, being founded on a primary thermometry approach, requires no calibration or reference, and so in principle could achieve reliable long-term *in-situ* thermodynamic temperature measurement without the intervention of national measurement institutes (though the measurement system may require periodic performance checking). Here we describe our approach and report on initial proof-of-concept investigations with alkali metal vapour cells. Our focus is to develop long-term stable reliable thermometers based on DBT that can be used in non-transmutative environments to reliably measure temperatures for long periods and in environments where sensor retrieval for recalibration is impractical such as in nuclear waste storage facilities.

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Progress toward driven optomechanical thermometry

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Optomechanical thermometry has recently emerged as a potential platform for realizing the kelvin at chip-scale, particularly at cryogenic temperatures. In such optomechanical thermometers, quantum noise provides an *in situ* calibration of the thermal motion of a mechanical oscillator via measurement of the optical Raman sidebands. Beyond cavity optomechanics, measuring the asymmetry in Raman spectra is used for optical thermometry in contexts such as distributed optical fiber sensors, combustion chemistry, and ultracold atomic physics. While the Raman scattering technique can be operated as a primary thermometer, it is rarely done because of the difficulty in calibration of the optical dispersion and absorption of the beam path, cavities, and filters, as well as asymmetries in the optical detection system. In our optomechanical system, detuning of the readout laser from the thermometer's optical cavity leads to systematic uncertainty in the measured temperature. The readout laser stabilization requirements increase experimental complexity and are a significant obstacle to high-precision primary optomechanical thermometers.

We present progress toward a simpler optomechanical thermometer, which will use an external mechanical driving force for *in situ* calibration. We derive the two-sided displacement power spectral density for a driven optomechanical thermometer, including externally driven, thermal, and quantum motion. The external drive allows separation of systematic effects, due to imperfect laser stabilization, from the thermal signal. We have developed GaAs nanobeam optomechanical crystals, since the piezoelectric effect in GaAs allows application of the driving force with a microwave probe. Two types of nanobeam devices have been fabricated: the first type uses on-chip electrodes to directly apply a piezoelectric force to the nanobeam, while the second type uses interdigital transducers to drive the nanobeam via surface acoustic waves. We characterize the driven motion of both device designs and explore their merits for driving an optomechanical thermometer. We also discuss integration of optomechanical and photonic thermometers for comparisons of their performance at cryogenic temperatures.

External sound card based practical Johnson noise thermometer

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In this paper, the design of a practical Johnson noise thermometer is presented. Theory of operation is similar to that presented in [1]. The main difference lies in the different injection of the reference signal into the system. The presented design uses a wideband transformer with a transformation ratio of 15625:1 for injecting reference signal instead of resistors, similar to the one in [2]. The reference signal is an optimized multisine signal with low crest factor [3]. This is important because this type of signal makes better use of the available dynamic range and minimizes distortion. The analog part of the thermometer is completely galvanically isolated from the rest of the measurement system including the analog-to-digital converter (ADC) and the digital-to-analog converter (DAC). A sound card was selected for ADC and DAC. The selected sound card (RME ADI 2 Pro FS R BE) has all the characteristics necessary for measuring the voltage ratios. The reference signal of the DAC was measured with a multimeter (HP 3458A) to account for the non-ideal voltage reference of the sound card. The thermometer's probe is designed to withstand temperatures of 300 ℃. The analog front end consists of two amplifiers of the same design, but separated from each other. This separation includes different battery power supplies, enclosures, cables from the sensor and cables to the DAC. The system can measure Johnson noise up to 300 kHz, which is limited by the sampling frequency of the sound card. The analog front end is intentionally limited to a bandwidth of 1 MHz to minimize amplification of EM interferences. Preliminary measurement results of the presented measurement system prototype will be presented in the final version of the paper.

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Tolerance stack-up for multi-component thermocouple circuits

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A practical thermocouple circuit typically includes multiple components between the measuring junction and readout device to facilitate installation and maintenance. For example, a circuit may include a mineral-insulated, metal-sheathed (MIMS) thermocouple probe, flexible extension cable and mating connectors. More complicated circuits may include a plurality of probes connected in electrical parallel to provide an output representing an average temperature. Each of these components contribute to the circuit output depending on the end-to-end temperature profile. Standard specifications such as ASTM E230 [1] and IEC 60584-1[2] describe the thermocouple output and tolerances for letter designated thermocouples. These standards apply to a single cut of thermocouple material tested with reference junction at 0 °C. However, for the circuit describe above, the components are usually made from different material lots and exposed to an arbitrary thermal profile. Although the nominal output of the circuit is often aligned with the industry standard, the tolerance varies depending on the components and thermal boundary conditions. There is no recognized standard that provides guidance how to estimate the output tolerance when the circuit is comprised of multiple components.

In this paper, an analysis method is presented to calculate the tolerance stack-up for a multi-component thermocouple circuit. A tolerance allocation criterion is proposed based on the thermocouple material tolerance class and temperature difference across the component. The method can be applied to circuits of varying complexity including a single thermocouple or multiple thermocouples connected in electrical parallel. The combined tolerance, along with the contributions of variance, provide insight how to improve the thermocouple circuit accuracy. The method is demonstrated using an example Type K thermocouple circuit. Experiences with thermocouple connectors and their contribution to overall system accuracy is also discussed.

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Drift of dual wall type N thermocouples: a study on the effect of dual wall geometry

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Dual wall thermocouples (Fig. 1) have been developed at the University of Cambridge in order to reduce the drift of mineral insulated metal sheathed thermocouples. A first design of the new sensor, herein called standard dual wall, was selected in the first development phase and used for several years. This version of the dual wall thermocouple is characterized by a certain inner wall to outer wall thickness ratio which determines the geometry of the sensor: the improved performance of standard dual wall thermocouples in terms of drift compared to conventional mineral insulated metal sheathed thermocouples was already demonstrated in previous investigations. In this study an attempt was made to understand the effect of the dual wall geometry on the performance of the thermocouples: for this purpose 3 additional customised dual wall type N mineral insulated cables, having different inner wall to outer wall thickness ratios, were designed and manufactured. Tests at 1150°C and 1200°C were undertaken in isothermal and thermal cyclic conditions. The results were compared with standard dual wall type N thermocouples and conventional type N thermocouples and related comments on the effect of the dual wall geometry on the drift and durability of the sensors are reported.

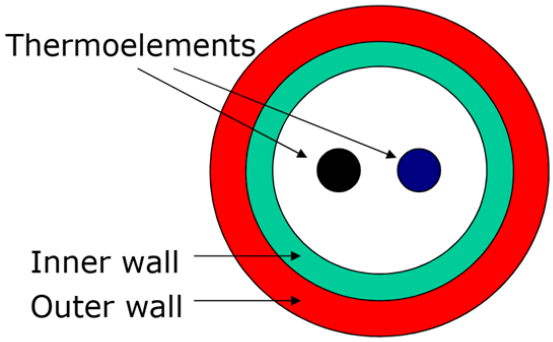

Fig. 1. Schematic drawing of a cross section of the dual wall thermocouple.

Different methodologies for the assessment of thermocouple drift: a study on mineral insulated metal sheathed type N and type K thermocouples

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This paper describes two different methodologies for the assessment of drift of thermocouples. The first methodology is based on the comparison between the signals of two thermocouples: one sensor is the thermocouple under test and the other is a reference sensor, often a Pt based thermocouple, which is supposed to be driftless in the test conditions. This methodology is the most frequently used. An alternative approach to estimate the drift of a sensor relies on measurements in fixed point cells before and after the exposure of the thermocouples at high temperatures. In this study the second methodology was applied to mineral insulated metal sheathed type N and type K thermocouples exposed at 1150°C in thermal cyclic conditions: an Fe-C fixed point cell was used for the assessment of drift. The results were compared with the drift measured against a reference Pt based thermocouple. Both conventional and dual wall type K and type N thermocouples having various dual wall geometries were included in the study. The advantages and disadvantages of the two methodologies are discussed in the paper.

An investigation at high temperatures on the insulation resistance of mineral insulated metal sheathed type K thermocouples having different MgO compositions and different diameters

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This paper summarises the results of an investigation undertaken at ISOMIL on the insulation resistance of mineral insulated metal sheathed type K thermocouples. The tests were designed to characterize the behaviour of these sensors at high temperatures: in particular measurements were undertaken at 800°C, 1000°C, 1200°C and 1300°C. Mineral insulated cables having MgO of 3 different purity were manufactured and for each MgO purity the insulation resistance at 4 different diameters between 1mm and 6mm was measured. Furthermore, two different techniques for the measurement of the insulation resistance were used: the first method relies on the application of high voltages between one thermoelement and the sheath, the second approach is based instead on the use of a current source. Their results are compared and the advantages and disadvantages of the two techniques are highlighted and discussed. The data presented in this paper allows to comment on the current test procedures described in technical standards and associated recommendations and to identify potential improvements to the current technical guidelines in relation to the insulation resistance of mineral insulated cables.

Evaluation of the Realization of Rh-C Eutectic Point for the Thermocouple Calibration

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In industry, high-temperature thermocouples are widely used for realizing precise temperature control applied to maintain the quality of products that are subject to annealing process at high temperature. For accurate temperature measurements, stable fixed points are usually used as reference to calibrate them. The metal-carbon eutectic points were investigated as the practical fixed points for the calibration of thermocouples in high temperature [1]. The rhodium-carbon (Rh-C) eutectic point (1657 °C) is considered as a useful practical fixed point for accurate calibration of thermocouples. However, there is still limited information about the Rh-C eutectic point at the present time.

In this work, a long Rh-C cell was constructed in our laboratory. The length of the cell was 243 mm, which is sufficiently long to ensure that sufficient immersion is available to decrease the influence of surrounding temperature, and to evaluate the inhomogeneity of the thermocouples. For the construction of the cell, the graphite crucibles were baked at 2000 °C for 3 hours in vacuum before being filled with rhodium and carbon powder. The nominal purities of rhodium and carbon powder are 99.995% and 99.9999%, respectively. The crucible and its content were heated until the content completely melted at the eutectic melting point under vacuum, and then cooled to room temperature. This process was repeated until the crucible was fully filled with alloy ingot. After filling, the Rh-C cell contained 408 g of eutectic alloy.

After the complete construction of the Rh-C cell, the repeatability of the melting and freezing curves as shown in Fig. 1, the effect of the surrounding temperature, and the heat flux effect in the cell were evaluated. Furthermore, the uncertainty of platinum-rhodium alloy thermocouples calibrated at the Rh-C eutectic point was estimated, including the uncertainty of the measuring system, the stabilities and the inhomogeneities of the thermocouples.

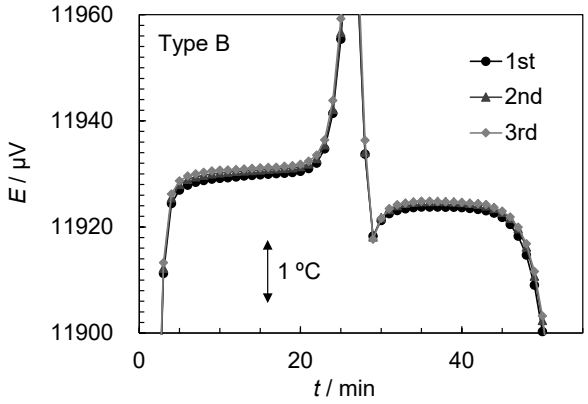

Fig. 1. The melting and freezing curves of Rh-C alloy.

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Development of an experimental device and a procedure for testing thermocouple inhomogeneities

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Thermoelectric inhomogeneity is the spatial variation of the Seebeck coefficient along a thermoelement. This is generated by the presence of impurities in the thermocouple metals.
The literature mentions thermocouple in-homogeneities as an important contributor to uncertainty and suggests scanning thermocouples [1]. In the case of non-new thermocouples, probably more contaminated, a greater effect is expected.
For cost-benefit reasons, the usual practice is not to recalibrate base metal thermocouples. It is not always the case in all countries; or at all times, and there are situations in which constant recalibration of these thermocouples is necessary.
Inhomogeneity studies carried out during the calibration of thermocouples in our laboratory show variations much higher than those bibliography suggested. The experimental results show us differences of around 10 °C and even some greater than 15 or 20 °C due to the exposure of the thermocouple to different temperature profiles.
In the Industrial Thermometers laboratory of the INTI Department of Thermodynamics, an automated device was developed to scan thermocouples and this test was carry out on a set of 48 thermocouples (38 base metal and 10 noble metal).
This paper shows the construction of the experimental device and its application procedure. Additionally, based on the data analysis of the 48 tests carried out. It will be analyzed if there is a relationship between the result of the measurements and the characteristics of the thermocouple (for example, diameter of the wires, hours of exposure to a certain range of temperatures, mechanical alterations of the sheaths, etc.).

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A Type J Thermocouple Proficiency Test

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A thermocouple proficiency test was performed for eight 17025 accredited laboratories in the United States spanning the temperature range of 100 °C to 700 °C, with NIST acting as the pilot lab. We chose to characterize a lot of bare type J thermocouple wire, since type J thermocouples are one of the most widely used temperature sensors in industry and NIST had already performed a similar type K proficiency test.

Cuts of wire were calibrated from both ends of the spool and these data were used to create reference values. Further cuts from the lot were used to make the transfer standards, with each participant receiving two thermocouples or cuts to construct two thermocouples (if they had in house facilities to do so). Since testing of base metal thermocouples is generally considered destructive over this temperature range, the transfer standards were not retested at NIST.

The skills and facilities necessary for testing of type J thermocouples are also applicable to the testing of other base metal thermocouples, and, to a lesser extent, testing of platinum-rhodium alloy thermocouples. As such, this was an opportunity for the laboratory to demonstrate not just their ability to calibrate type J's but their ability to calibrate thermocouples in general.

This poster will describe the preparation, protocol, and results of the proficiency test.

Hybrid Comparison of Co-C Eutectic Fixed Point Cells for Thermocouple Calibration

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Accurate high-temperature measurement is essential for many industrial and scientific applications. Thermocouples are the most common type of sensors used for temperatures above 1000 °C. For new (i.e. unused) noble metal thermocouples (Type R, S and B) which need to comply with the relevant standard specifications, the best possible calibration should be performed to confirm the tolerance, which should be within ± 3.25 °C at 1300 °C according to IEC 60584-1 (Class 2 tolerance). At this high temperature, Co-C eutectic fixed point cells (melting point 1324 °C) offer the possibility of significantly lower uncertainties than can be achieved with pure metal fixed points, and have been employed for thermocouple calibrations [1]. The best way to assign the temperature of the Co-C eutectic cells is by radiation thermometry or by more than one fixed-point cell intercomparison [2]. However, for NMIs that have only one commercially calibrated Co-C cell and are on the way to establishing conventional fixed point cell realization, the hybrid comparison could be a possible way to maintain the traceability of their thermocouple calibration service.

In this study, we describe the way to maintain the traceability of the NIMT Co-C fixed point by using the same Pt/Pd thermocouple as a transfer standard by means of a hybrid method (calibration and comparison) to compare the relative temperatures of several different Co-C eutectic fixed-point cells, specifically those from NPL, NIMT, and PTB.

The repeatability and stability of the transfer standard thermocouple(s) were investigated by measurements at the freezing point of copper before and during calibration in different Co-C cells. In addition, the thermoelectric drift and inhomogeneity characteristics of the transfer thermocouple, after use at this high temperature, are also investigated.

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Closing Plenary Session P: The Future of International Temperature Scales

Future of the International Temperature Scale
Patrick M.C. Rourke (National Research Council Canada, Canada)
Invited

Invited

Future of the International Temperature Scale

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The International Temperature Scale of 1990 (ITS-90) was intended to be more reproducible and easier to use than primary thermometers, while still providing scale temperatures T_{90} that closely approximate thermodynamic temperature T. This defined scale has successfully underpinned thermometry worldwide for over three decades.

But times are changing.

Encouraged by the 2019 redefinition of the kelvin, some National Metrology Institutes (NMIs) are moving toward direct dissemination of T. The case for this is strongest at the extremes of temperature, where ease of use and reproducibility of the ITS-90 are worst. Over time, the temperature ranges accessed by client-facing primary thermometry are expected to grow.

However, the anticipated transition from T_{90} to T dissemination will be jagged and incomplete, at least on the scale of several decades: a constantly shifting patchwork of overlapping defined scale and thermodynamic temperature dissemination around the world as the primary thermometry capabilities of different labs come online and evolve. Even the largest NMIs will likely continue doing ITS calibrations across at least some of the core long-stem standard platinum resistance thermometer range. Many other NMIs and commercial calibration laboratories may not gain the ability to directly disseminate T at all.

In such a global mixed dissemination environment, it is clear that an International Temperature Scale will continue to be used for a long time. So what is its current state of the art and where does this lead us for the future?

The best knowledge of the reproducibility and thermodynamic accuracy of the ITS-90 will be reviewed, with present challenges placed in context of the goals aspired to by the scale creators. With this ITS-90 “best self” in mind, the scale implications of the foreseen global mixed dissemination environment will be explored, highlighting the pre-existing pain points that stand to be both alleviated and aggravated.

It is now possible to evolve the ITS into the temperature scale that the ITS-90 creators were trying to make in the first place. In doing so, the scale could be meaningfully improved for its many long-term users while also embodying a more harmonious position within the mixed dissemination environment. The specific set of changes that this would entail will be evaluated in terms of benefits, costs and work still to do.

ITS10 Workshops

Introduction to Contact Thermometry, Theory and Practice

Part 1: Fundamentals, Scales and Standards
Weston L Tew, Jr (National Institute of Standards and Technology, USA)

Part 2: Thermocouple Thermometry
Karen Garrity (NIST, USA)

Part 3: Calibration Methods and Industrial Sensors
Dawn Cross (National Institute of Standards and Technology, USA)

Introduction to Humidity and Trace Moisture Measurement

Part 1: Fundamentals
Christopher Meyer (National Institute of Standards and Technology, USA)

Part 2: Humidity Generators
Christopher Meyer (National Institute of Standards and Technology, USA)

Part 3: Hygrometers
Christopher Meyer (National Institute of Standards and Technology, USA)

Fundamentals and Applications of Radiation Thermometry

Part 1 Fundamentals and Blackbody sources
Howard Yoon (NIST, USA)

Part 2: Radiation Thermometers
Howard Yoon (NIST, USA)

Part 3: Part 3 Radiation Thermometers Using Blackbody Sources
Howard Yoon (NIST, USA)

Introduction to Contact Thermometry: Theory and Practice

Weston Tew[1], Karen Garrity[1], Dawn Cross[1]
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This tutorial will cover the fundamental aspects of contact thermometry and the practical aspects of common temperature sensors, including calibration methods. The methods discussed will span temperatures from -200 °C to +2000 °C. The theory behind temperature measurement and temperature scales will be reviewed. The technology supporting both standard- and common industrial-temperature sensors and temperature measurement systems will be discussed. Detailed guidance on the use of platinum-based resistance thermometers and noble-metal thermocouples will be provided. The design and practical role of fixed-point cells will be presented. Practical aspects of thermometer calibration and best practices will be shown. The sessions will introduce the subject for the new practitioner.

The intended audiences are engineers, technicians, and scientists involved in special test, calibration and quality control in common laboratory settings as well as those working in thermodynamic product development and related applications.

Part 1 Fundamentals, Scales and Standards, Instructor: Weston Tew

We will discuss the concept of temperature and its fundamental role in thermodynamics, with an emphasis on thermal equilibrium and heat transfer in physical systems. The concept of temperature scales and units will be reviewed. The general practice of contact thermometry will be developed from the standpoint of systems in equilibrium. The concepts, practical realizations, and fundamental roles of fixed points in temperature metrology will be explained in detail. The theory and practice of Platinum Resistance Thermometry will be reviewed with examples taken from the current state of the art and commercial technology. The ITS-90 will be reviewed and its mathematical structure explained with examples taken from common laboratory practice.

Part 2 Thermocouple Thermometry, Instructor: Karen Garrity

This 90-minute session will focus on thermocouples, spanning a temperature range from 0°C up to 2200 °C. We will discuss the various types of thermocouples construction and principles of operation. Additionally, we will discuss their diversified uses as well as methods of calibrations. Methods of calibration will include the operation and application of fixed-point cells in the thermocouple laboratory. Finally, a short discussion on the care and handling of thermocouple will be provided.

Part 3 Calibration Methods and Industrial Sensors, Instructor: Dawn Cross

During this 90-minute session, we will have an overview of each type of thermometer (digital, thermistor, and industrial platinum resistance thermometer) their characteristics, and touch on the expected uncertainties. Selecting a thermometer for your specific application will be discussed. Calibration techniques and measurement validation methods will be covered.

Instructor Biographies

Weston Tew has held the position of staff physicist in the NIST Sensor Science Division since 2011 working on special applications in temperature measurement, new fixed points, high-temperature thermocouples, 3D thermomagnetic imaging, consensus standards and conformity assessment. From 1993-2010 he served as a staff physicist in the NIST Process Measurements Division working on temperature sensors and interpolation, cryogenic fixed points, noise thermometry, and isotopic effects in phase equilibria. He is a former National Research Council postdoctoral Associate at NIST where he performed research on quantum-based current sources and the Kibble balance. Dr. Tew is an author/co-author of over 85 papers on these subjects and holds two patents. Prior to his work at NIST, Tew worked as a guest researcher at the BIPM in Sevres France. He is a recipient of the US Department of Commerce Bronze Medal and the ASTM Award of Merit. Dr. Tew is a member the International Electrotechnical Commission, Working Group 5 on Temperature Sensors of the IEC subcommittee 65B. He is also a Fellow of the ASTM and Chair of the subcommittee E20.07 on Temperature Measurement Fundamentals.

Karen Garrity has performed thermocouple calibrations and research in the NIST thermocouple laboratory for 22 years. Her duties include calibrations of noble metal thermocouples, base metal thermocouples, and refractory metal thermocouples by comparison and fixed-point methods. She is also responsible for building freezing-point cells for the laboratory. She has led several international thermocouple comparisons as well as providing thermocouple NVLAP proficiency tests. She has published papers on thermocouple performance and uncertainties, thermocouple comparison, and improved furnace designs. She actively participates in ASTM (American Society of Testing and Materials). She has taught at the SIM Metrology School and at the NIST MSC tutorials on the use of thermometers. She is a technical assessor for the NIST Sensor Science Division.

Dawn Cross recently retired from the National Institute of Standards and Technology (NIST) after 40 years of service. Dawn was responsible for the Industrial Thermometer Calibration Laboratory (ITCL) calibration of industrial platinum resistance thermometers, thermocouples, thermistors, digital thermometers over the range of -196 °C to 550 °C. As part of her responsibility for the ITCL, Dawn maintained the NIST quality system documentation and measurement assurance to maintain compliance with the NIST Quality Manuals (QM) and ISO/IEC 17025;2017. Cross has served as a NVLAP assessor since 2005 for NIST and 2008 for outside laboratories, and now does contracting work with NVLAP. When she was not performing calibrations, Cross performed temperature research related to the uncertainty of industrial thermometer calibrations and finding alternatives to Hg-in-glass thermometers. Additionally, Dawn performed NIST technical assessments covering the areas of temperature (contact and non-contact), ceramics, pressure and vacuum, and fluid flow. To maintain visibility and protect the interests of NIST and U.S. industry, she served on several national standard committees within ASTM E20 (Thermometry) and committees within NIST. She was the Sub-Chairman for ASTM E20.03 Resistance Thermometers Sub-Chairman for ASTM E20.05, Liquid in Glass Thermometers and Hydrometers, and a member of ASTM D.02 Petroleum Committee. Cross has taught courses at the Measurement Science Conference (MSC) Symposium, 2010, 2011, 2013, 2015, 2016, 2017, 2018, 2019, 2022 covering SPRT's, LiG's, PRT's, Thermistors, and thermocouples.

Introduction to Humidity

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Humidity is not a single quantity but a family of quantities that involve moisture content in a gas, including relative humidity, dew point, water amount fraction, and water mass ratio. This course will teach the fundamentals of these quantities and explain how they relate to each other and are influenced by other quantities, such as temperature and pressure. Applications requiring accurate measurement and/or control of humidity will be discussed. The course will also discuss humidity generators and how they can be used as primary standards for water amount fraction and dew point for calibration of hygrometers. It will show how a humidity generator can be combined with a temperature-controlled chamber to make it a primary standard for calibration of relative humidity sensors. The NIST primary standard humidity generator will be fully described as an example of the type of generators found in national metrology institutes. Finally, the course will describe the different types of instruments used to measure quantities in the humidity family, including chilled mirror hygrometers (dew point), capacitance sensors (relative humidity), psychrometers (relative humidity), and cavity ringdown spectrometers (water amount fraction).

Part 1 Fundamentals

We will introduce the water phase diagram. Humidity-related concepts such as the water partial pressure, saturated water-vapor pressure, saturated ice-vapor pressure and the water-vapor enhancement factor will be discussed. Also, we will describe how some these quantities are a function of temperature and pressure. We will explain how humidity is not a single quantity but a family of quantities involving moisture content in a gas, including water amount fraction, water mass ratio, dew point, frost point, and relative humidity. Water amount fraction in a carrier gas is the most fundamental humidity quantity and is defined as the fraction of water molecules to the total number of molecules in a given volume. Water mass ratio is the ratio of the mass of water molecules to the mass of carrier gas molecules in a given volume. Dew point (frost point) is the temperature at which water (ice) saturation in a carrier gas occurs; below this temperature H_2O condenses as water (ice) and is a function of the water amount fraction and the pressure. Relative humidity is defined as the water amount fraction divided by the water amount fraction at saturation and is a function of the water amount fraction and temperature. In this workshop we will describe these humidity quantities in more detail and explain how they relate mathematically to each other and to temperature and pressure.

Part 2 Standard Humidity Generators

We will describe the basic design of a saturator, a chamber containing water or ice over which a carrier gas flows until it is saturated with water vapor. We will explain how saturators are the centerpiece of most humidity generators, and how these generators are used to calibrate hygrometers. We will explain the different methods used in humidity generators, including the single-pressure, two-pressure, and divided-flow methods. Generators using the single-pressure method consist of a temperature-controlled saturator with gas flowing through it that is at approximately the same pressure as that applied to the hygrometer. The generated dew/frost point is changed by varying the temperature of the saturator. In the two-pressure method, the pressure inside the temperature-controlled saturator may be elevated to be higher than that applied to the hygrometer, because the saturator is separated from the hygrometer by an expansion valve. In this case, the dew/frost-point can be changed by varying the saturator pressure as well as the saturator temperature. The divided-flow method mixes metered flows of moist gas (from a saturator) and dry gas. The generated dew/frost point is changed by varying the relative flows of the moist and dry gases. For calibration of

relative humidity sensors, the gas exiting the humidity generator is directed to a temperature-controlled test chamber containing the sensor and a reference thermometer. In this workshop, we will describe the NIST Hybrid Humidity Generator as an example of a standard humidity generator that uses both the two-pressure and divided-flow methods.

Part 3 Hygrometers

We will describe several types of instruments for measuring the different humidity quantities. First, we will discuss chilled-mirror hygrometers, which directly measure dew point and frost point. They achieve this measurement using a temperature-controlled mirror and an optical method for determining the presence of condensation on the mirror. The control system directs the mirror temperature to the point where condensation first occurs. An external thermometer can be used to measure the applied gas's temperature, which enables calculation of the relative humidity of the gas. Second, we will describe thermohygrometers, which measure both temperature and relative humidity in a probe. The relative humidity sensor in the probe directly measures an electrical property (capacitance or impedance) of a thin layer of moisture-absorbing material. The electrical property varies monotonically with the water partial pressure in the surrounding gas. Third, we will talk about psychrometers, which measure the temperature of a gas and the temperature depression of a wet wick in the gas due to evaporation; the temperature and temperature depression are used to calculate the relative humidity of the gas. Fourth, we will talk about cavity ringdown hygrometers, which use a laser absorption spectroscopy method to measure water amount fraction. Finally, we will discuss gravimetric hygrometers, which measure water mass ratio in a gas by separating the water from the gas and measuring the mass of each. While they are the most accurate hygrometers, they are only used in standards laboratories because their operation is too complex and time consuming for field measurements. The uses and relative merits of these five types of hygrometers will be described.

Instructor Biography

Chris Meyer has 33 years of metrology experience working at NIST in the areas of temperature, humidity, and pressure standards. He is an honor graduate of Haverford College and received his Ph.D. in physics from the University of California at Santa Barbara. Afterwards, he came to NIST as a postdoc, performing acoustic thermometry to obtain some of the most accurate thermodynamic temperature measurements ever made over the range 234 K to 303 K. Dr. Meyer joined the NIST Thermometry Group (Now the Thermodynamic Metrology Group) in 1991. His first project was to construct a facility to realize the International Temperature Scale of 1990 (ITS-90) over the low-temperature region (0.65 K to 84 K) using 3He and 4He vapor-pressure thermometry, gas thermometry, and platinum resistance thermometry. Since that time, he has worked in several other areas of thermometry, including wire thermocouples, digital thermometers, light-pipe radiation thermometers, and fluorescence thermometers. He has worked in the discipline of humidity since 2000. During this time, he helped develop the current NIST gravimetric hygrometer and the hybrid humidity generator (the US national standard for humidity). He used the gravimetric hygrometer to validate the performance of hybrid humidity generators and measure thermophysical properties of moist air and moist CO2). Chris has operated the humidity calibration laboratory since 2013. From 2017 to 2018, he spent 15 months working at the International Bureau of Weights and Measures (BIPM), helping develop a manometric system for determination of the amount fraction of CO2 in air. In 2018 Chris entered pressure metrology and now oversees the NIST piston gauge calibration laboratory. He is a recipient of the US Department of Commerce Bronze Medal and the ASTM Robert D. Thompson Memorial Award. Currently he is a member of the Consultative Committee on Thermometry (CCT) and active in CCT Working Groups WG-KC on Key Comparisons and WG-Hu on Humidity. He is also a member of ASTM Committee E20 on Temperature Measurement and it the chair of subcommittee E20.09 on Digital Contact Thermometers.

Fundamentals and Applications of Radiation Thermometry

Howard Yoon[1],
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This tutorial will cover the fundamentals and applications of radiation thermometry including Planck radiation law and properties of ideal and real blackbodies. Optical designs of radiation thermometers will also be discussed. Properties of radiation thermometers and characterizations needed to develop an uncertainty budget for radiation thermometer calibrations will be shown. We will cover the temperature range from – 50 deg C to 3000 deg C. The basic concepts will be illustrated with applied radiance temperature measurement examples from NIST calibration services and from NIST research involving radiation thermometer developments. The intended audiences of the tutorial are engineers, technicians, and scientists involved in radiation thermometer measurements and applications.

Part 1 Fundamentals and Blackbody sources

This first part of the radiation thermometry course will cover the fundamentals of Planckian radiation and the relationship to temperature scales. We will explore different types of blackbodies and their characteristics. We will examine how various types of blackbodies are used for realizing non-contact temperature scales. We will look at the concept of emittance and emissivity. A software program written by Peter Saunders of MSL (New Zealand) to calculate emissivities of blackbodies will be introduced and demonstrated. Students will be provided with their personal copy of this software.

Part 2 Radiation Thermometers

The second part of the radiation thermometry course will go over various radiation thermometer designs which can be used to cover the range of temperatures from -50 deg C to 3000 deg C. We will look at how different detectors and optics are used to construct standard radiation thermometers and how these radiation thermometers are used in calibrations of both other RTs and blackbodies. We will examine what types of characterization should be performed to assess the uncertainty components for these RTs used in calibrations. We will go over interpolation equations and the significance of fitting parameters.

Part 3 Radiation Thermometers Using Blackbody Sources

The third part of the radiation thermometry course will go over developing measurement uncertainties for both RT and blackbody calibrations. A brief introduction will be given to basic concepts in uncertainties. We will use the measurement equation approach to determining total uncertainties. This part will use information from the first and second parts of this course. Uncertainty budgets will be developed for several different measurement scenarios.

Instructor Biography

Howard Yoon is the Group Leader of the Optical Radiation Group in the Sensor Science Division at NIST. His group is responsible for both source and detector standards from the vacuum UV to the thermal infrared wavelength regions. He is also the US national representative for thermometry on the Consultative Committee for Thermometry (CCT) at the BIPM and is also a long-standing member of the CCT working group on non-contact thermometry. He has authored or coauthored over 130 technical publications, mostly in the areas of spectroradiometry and radiation thermometry. He has 3 US patents and one pending patent application. He has twice won the NIST Astin award for measurement science and was also the recipient of the Department of Commerce silver medal for scientific achievement. He received his Ph.D. in solid-state physics specializing in optical spectroscopy from the University of Illinois at Urbana-Champaign.

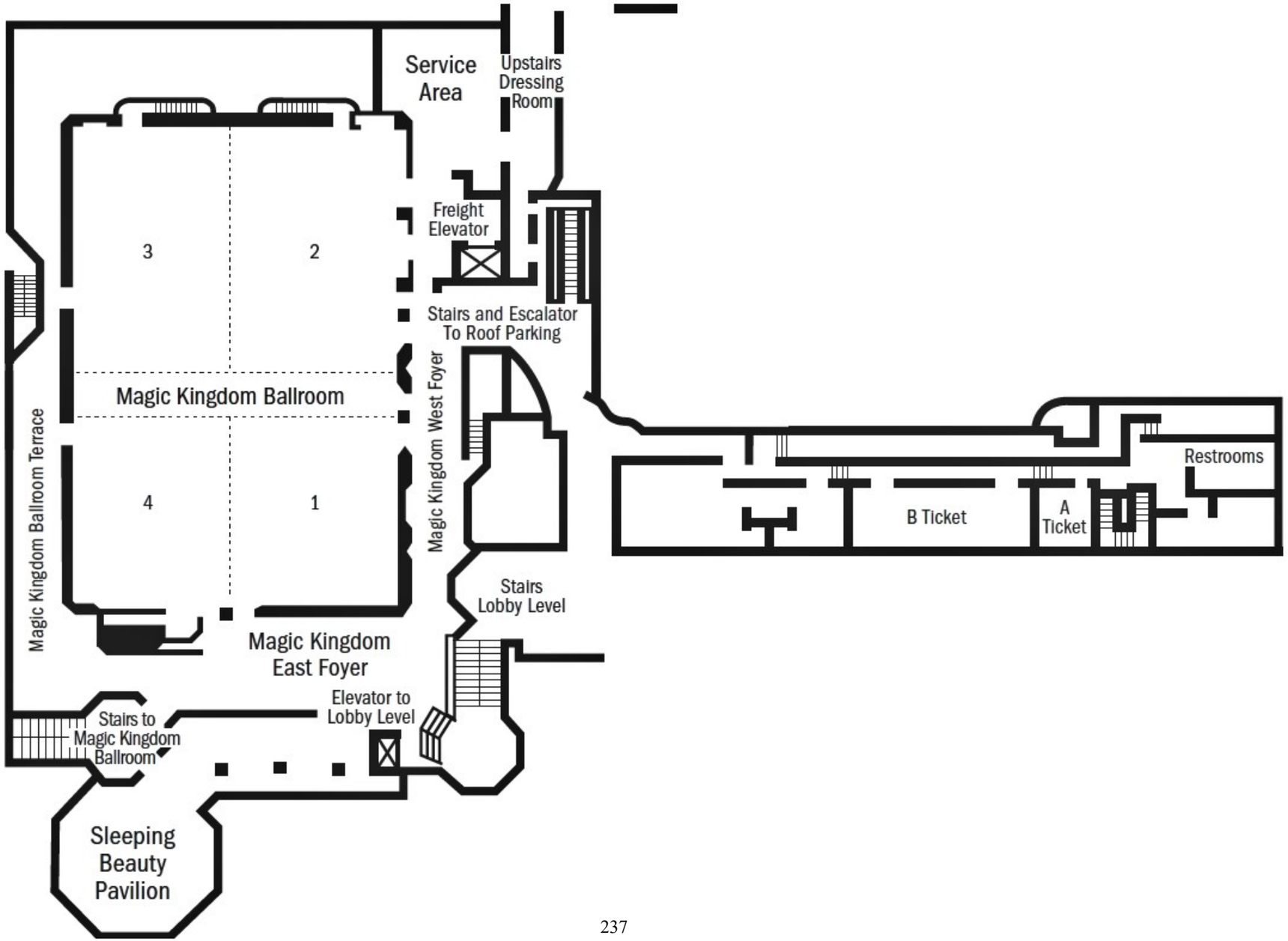
Appendix A. Conference Program, Visuals, and Map

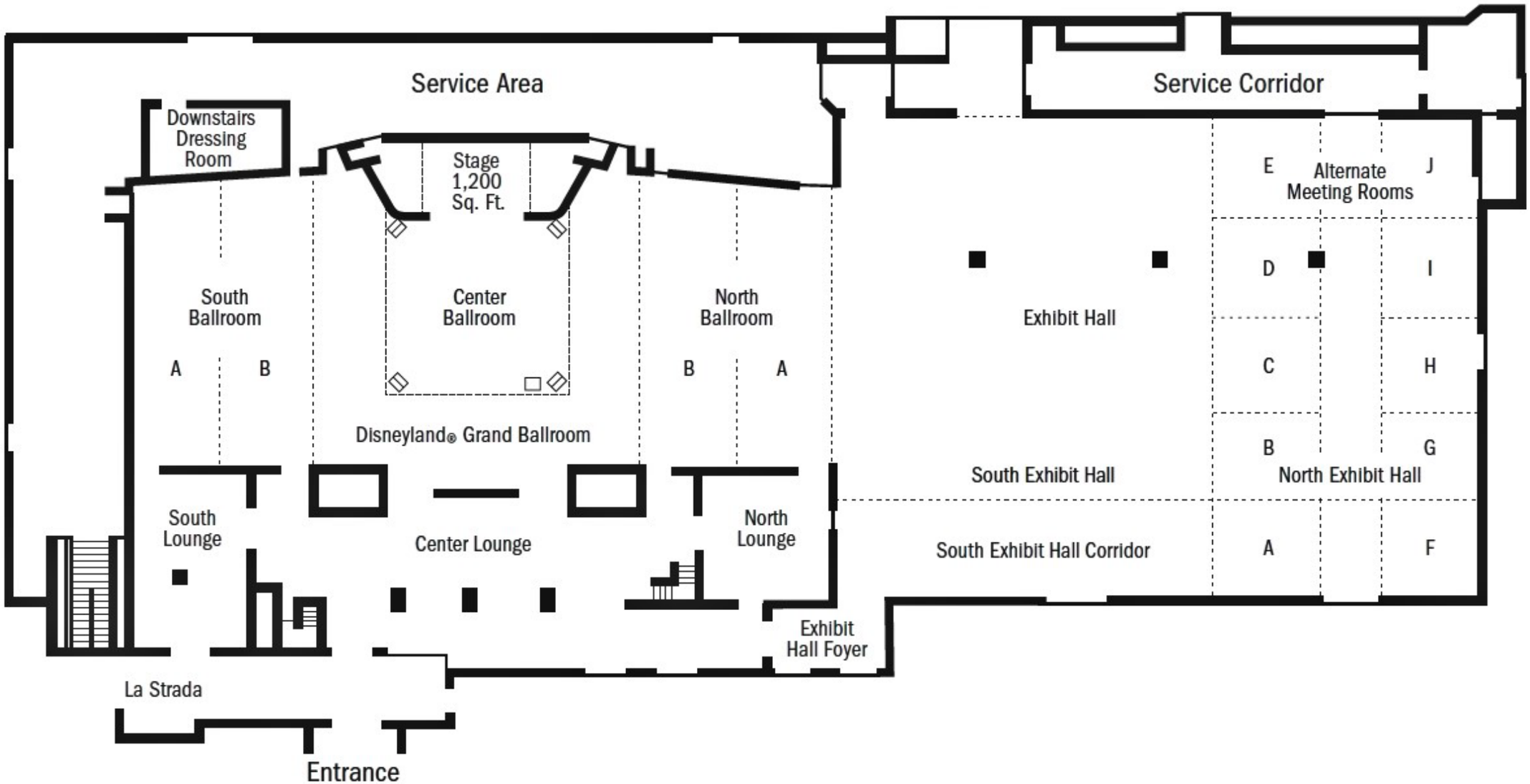
Included visuals

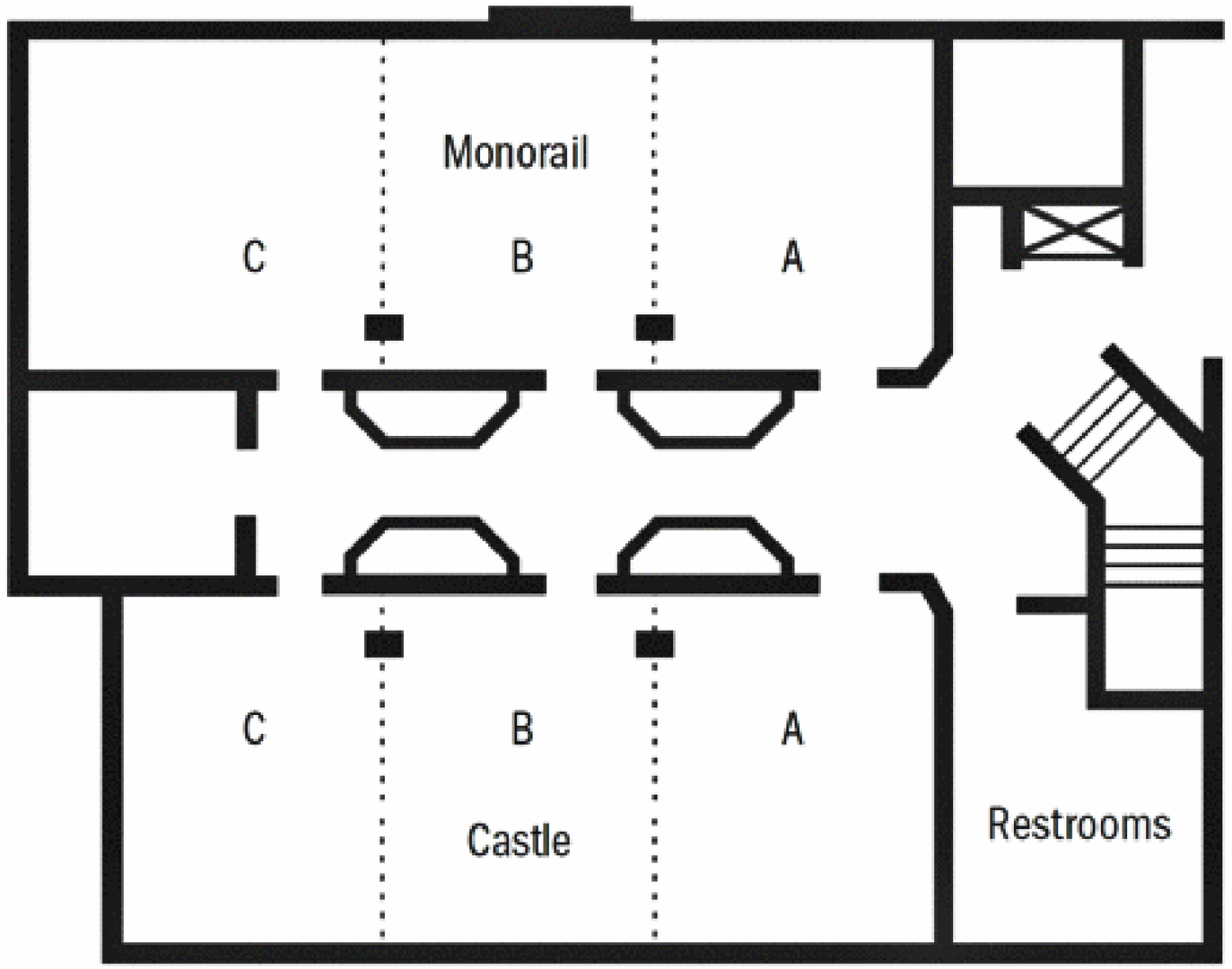
- Conference Program Synopsis
- Conference Center Upper Level
- Conference Center Lower Level
- Monorail Castle
- Exhibit Hall
- Poster Locations within Exhibit Hall

Program for *10th International Temperature Symposium*

Time	Magic Kingdom 1	Magic Kingdom 2	Magic Kingdom 3	Magic Kingdom 4	Exhibit Hall	Castle C	Castle B
Tuesday, April 4							
08:30-10:00		A: *Opening Plenary Session: James F Schooley Plenary Lecture*					
10:00-10:45	*Break*						
10:45-12:15	B-1: *Thermodynamic Temperature 1*	B-2: *Radiation Thermometry I*	B-3: *Luminescence Thermometry*	B-4: *Humidity Standards*		B-5: *ITS10/MSC Workshop: Introduction to Contact Thermometry, Theory and Practice*	
12:15-13:45	B-C: *Lunch*						
13:45-15:15		C: *Tuesday PM Plenary: Frontiers in Temperature Measurement*					
15:15-16:00	*Break*						
16:00-17:30	D-1: *Realizing the Redefined Kelvin (Real-K)*	D-2: *Radiation Thermometry - Emissivity*	D-3: *Platinum Resistance Thermometry*	D-4: *Photonic Thermometry*		D-5: *ITS10/MSC Workshop: Introduction to Contact Thermometry, Theory and Practice*	
Wednesday, April 5							
08:30-10:00		E: *Wednesday Plenary Session: Trends in Industrial Temperature Measurement*					
10:00-10:45	*Break*						
10:45-12:15	F-1: *Non-metal Fixed Points I*	F-2: *High Temperature Fixed Points*	F-3: *Digitization and Automation*	F-4: *Photonic methods for Trace Moisture and Humidity Measurements*		F-5: *ITS10/MSC Workshop: Introduction to Contact Thermometry, Theory and Practice*	
12:15-13:45	*Lunch*						
13:45-15:15	G-1: *ITS-90 Fixed Points*	G-2: *Thermal Imaging*	G-3: *New Technologies for Harsh and High Temperature Process Measurements*	G-4: *Low Temperature Thermometry*		G-5: *ITS10/MSC Workshop : Introduction to Humidity and Trace Moisture Measurement*	
15:15-16:00	*Break*						
16:00-17:30					H: *Poster Session I*		
Thursday, April 6							
08:30-10:00		I: *Thursday Plenary: Temperature, Climate and Human Health*					
10:00-10:45	*Break*						
10:45-12:15	J-1: *Triple Point of Water*	J-2: *Radiation Thermometry - II*	J-3: *Thermocouples - Base Metal and Refractory*	J-4: *Air Temperature for Meteorology and Aviation*		J-5a: *ITS10/MSC Workshop : Introduction to Humidity and Trace Moisture Measurement*	J5b: *ITS10/MSC Workshop: Fundamentals and Applications of Radiation Thermometry*
12:15-13:45	*Lunch*						
13:45-15:15	K-1: *Thermodynamic Temperature II*	K-2: *Satellite-based Earth Temperature Monitoring*	K-3: *Thermocouples II*	K-4: *Bio-medical Thermometry*		K-5a: *Introduction to Humidity and Trace Moisture Measurement*	K-5b: *Fundamentals and Applications of Radiation Thermometry*
15:15-16:00	*Break*						
16:00-17:30					L: *Posters II*		
Friday, April 7							
08:30-10:00	M-1: *Thermodynamic Temperature III*	M-2: *Spectroscopic and Photonic Temperature Measurement*	M-3: *Thermometry for Nuclear Envionments*	M-4: *Traceability, Uncertainty, and Genetic Algorithms*			M-5: *Fundamentals and Applications of Radiation Thermometry*
10:00-10:45	*Break*						
10:45-12:15					N: *Posters III*		
12:15-13:45	*Lunch*						
13:45-15:15		P: *Closing Plenary Session*					


Service Area
Upstairs Dressing Room
Freight Elevator
3
2
Stairs and Escalator To Roof Parking
Magic Kingdom Ballroom
Magic Kingdom West Foyer
Magic Kingdom Ballroom Terrace
4
1
Restrooms
B Ticket
A Ticket
Stairs Lobby Level
Magic Kingdom East Foyer
Elevator to Lobby Level
Stairs to Magic Kingdom Ballroom
Sleeping Beauty Pavilion


Service Area
Service Corridor
Downstairs Dressing Room
Stage 1,200 Sq. Ft.
E
Alternate Meeting Rooms
J
South Ballroom
Center Ballroom
North Ballroom
Exhibit Hall
D
I
A
B
B
A
C
H
Disneyland® Grand Ballroom
B
G
South Exhibit Hall
North Exhibit Hall
South Lounge
Center Lounge
North Lounge
South Exhibit Hall Corridor
A
F
Exhibit Hall Foyer
La Strada
Entrance


Monorail
C
B
A
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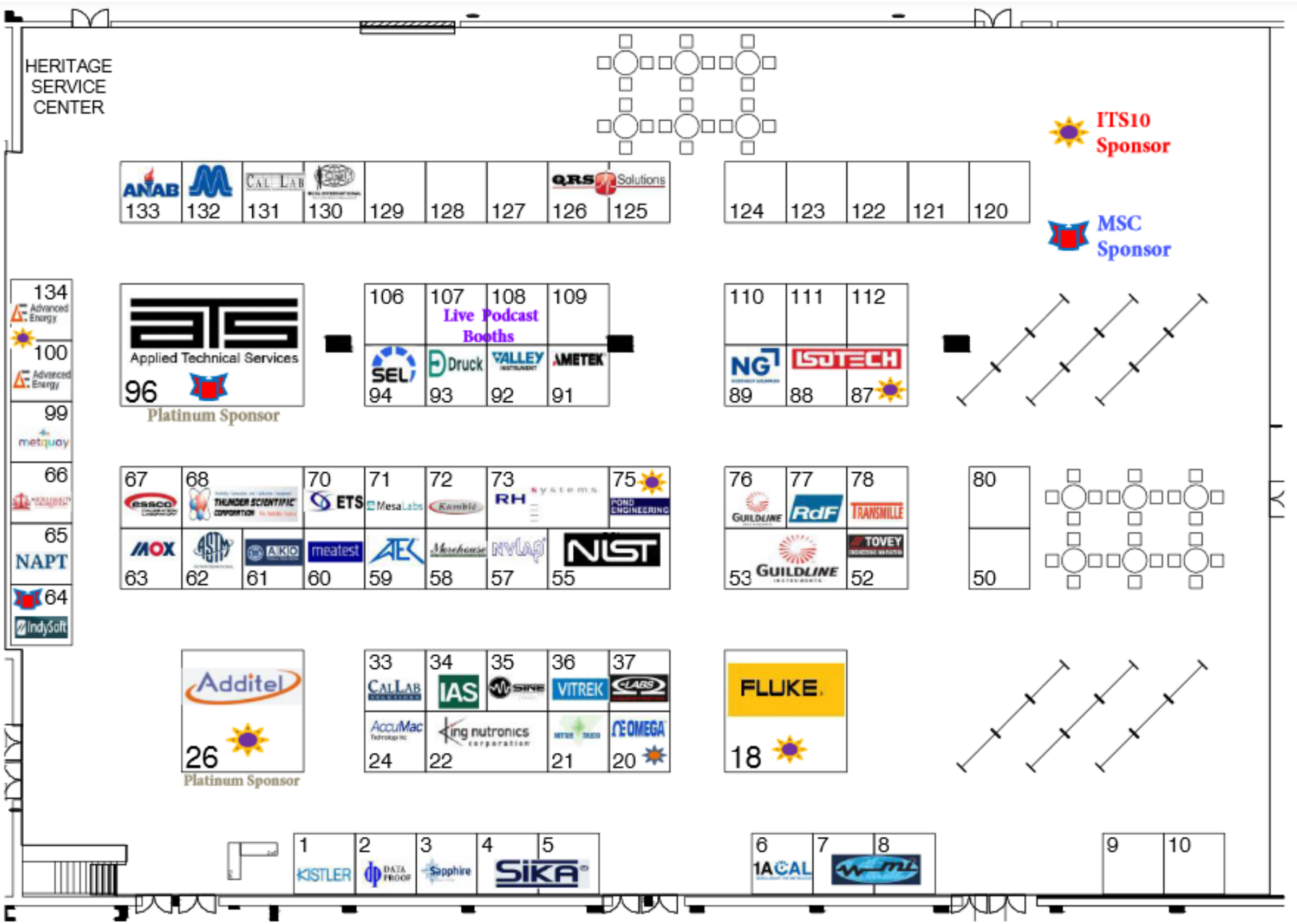
B
A
Castle
Restrooms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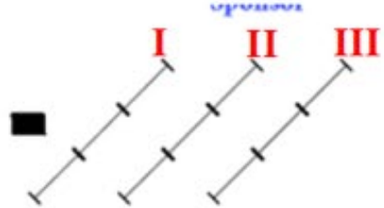
L-4	N-4	H-4	L-3	N-3	H-3
H-1	L-1	N-1	H-2	L-2	N-2

I



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H-5	L-5	N-5	H-6	L-6	N-6

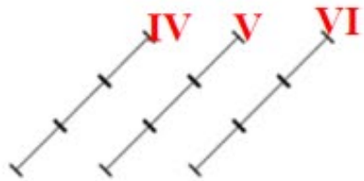
II

L-12	N-12	H-12	L-11	N-11	H-11
H-9	L-9	N-9	H-10	L-10	N-10

III

L-16	N-16	H-16	L-15	N-15	H-15
H-13	L-13	N-13	H-14	L-14	N-14

IV



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H-17	L-17	N-17	H-18	L-18	N-18

V

MAPS	N-25	N-24	blank	N-23	H-23
H-21	L-21	N-21	H-22	L-22	N-22

VI