

Progress report for EMRP project “High Temperature Metrology for Industrial Applications”; HiTeMS

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Abstract. This paper gives an overview of the progress with the European Metrology Research Programme (EMRP) project “High Temperature Metrology for Industrial Applications” (HiTeMS). The objective of the project is to address, on a broad front, a number of unsolved measurement challenges in the domain of high temperatures above 1000 °C, both in non-contact and contact thermometry. It brings together a total of 15 partner organisations; National Measurement Institutes (NMIs) (10), industrial companies (4) and a Fraunhofer Institute. The project started in September 2011 and will end in August 2014, though it is envisaged that the developments started here will have impact on industrial high temperature measurement long after the project is completed.

1 Introduction

The measurement of temperatures above 1000 °C is vital to ensure the success of a wide range of industrial processes. However ensuring measurement reliability and, in particular, traceability to the International Temperature Scale of 1990 (ITS-90) directly within the industrial process is very difficult, if not impossible in some industrial settings.

The project HiTeMS [1, 2] has been addressing this problem by developing a suite of methods and techniques which will significantly improve the practice of industrial high temperature non-contact and contact thermometry, up to at least 2500 °C. Special emphasis has been given to facilitating *in-situ* traceability and as such addresses issues such as unknown material emissivity, sensor drift and/or unquantified transmission changes.

HiTeMS is a three-year, fifteen partner project, part funded by the European Metrology Research Programme (EMRP). The project partners are: National Measurement Institutes; NPL, UK, (coordinator), Centro Español de Metrología (CEM) Spain, CMI, Czech Republic, LNE-Cnam, France, Istituto Nazionale di Ricerca Metrologica (INRIM) Italy, PTB, Germany, Slovak Institute of Metrology (SMU) Slovakia, Turkish National Metrology Institute (UME) Turkey, VSL, Netherlands; and industrialists; GDF-Suez (GDF) France, Meggitt Sensing Systems (MSS) UK, Commissariat à l’Energie Atomique et aux Energies Alternatives (CEA) France,

Endress+Hauser (E+H) Germany. In addition a Researcher of Excellence Grant (REG) was awarded to the Fraunhofer Institute for Material and Beam Technology (FhG) Germany that specializes in laser welding and materials processing. A second REG grant was awarded to the Bavarian Centre for Applied Energy Research (ZAE Bayern) after the project was started. The role of this sixteenth partner is to perform supporting emissivity measurements of materials typically encountered in the processes covered by HiTeMS.

The research is divided into six technical workpackages (WP1 to 6) each addressing a different unsolved temperature measurement problem. In brief these are:

For non-contact thermometry:

- Emissivity and reflected radiation, with the target of achieving *in-situ* traceability (WP1)
- Self-validation and corrections for varying window/path transmission, to approximately 2500 °C (WP4)
- Real time traceable temperature measurement in laser materials processing (WP5)

For contact thermometry:

- Lifetime assessment of base metal thermocouples and drift measurements of base and noble metal thermocouples (WP2)
- Self-validation and demonstrated *in-situ* validation for temperature sensors to at least 2000 °C (WP3)

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- Facility for determination of reliable reference functions for high temperature non-standard thermocouples (WP6)

The HiTeMS project started in September 2011 and progress in addressing the above identified problems has been made, though significant challenges remain. This paper will give an overview, in the context of the workpackages, of some of the highlights of the research to date.

2 WP1: Traceable and accurate measurement techniques for *in situ* surface high temperature measurement (>1000 °C)

WP1 addresses, or seeks to mitigate, the two problems of unknown surface emissivity and reflected radiation from high temperature sources. In addition it seems to quantify the effect of the size of source effect in the presence of extended large high temperature sources.

2.1 Characterization of a UV multi-wavelength high-temperature measurement system

Although doubt remains over the general validity of multi-wavelength pyrometry [3], recent modeling [4] has indicated that lower uncertainty temperature determinations may be possible provided the measurements are performed at as short a wavelength as practicable.

A temperature measurement system seeking to benefit from this approach, based on a commercial spectrometer and 1024 x 256 pixels CCD TE cooled detector, is currently undergoing characterization at INRiM (Figure 1). This will be used as a multi-wavelength thermometer operating in the UV-VIS-NIR spectral range (from 0.35 μm to 0.95 μm). The initial characterization involves determining the signal against the source temperature at different spectrometer configurations (i.e. different grating density, slit width and wavelength range).

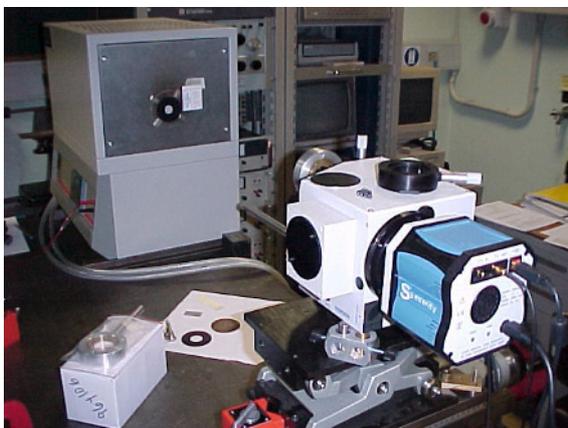


Figure 1. Measurement system for the multi-wavelength thermometer developed at INRiM. The system consists of HORIBA spectrometer and a TE-cooled CCD.

Further tests to confirm the agreement between the expected characteristics obtained from the modelling [4] and the real performance of the system are on-going. These tests consist of measurements of the readout noise, dynamic range, signal to noise ratio and nonlinearity. The results from the testing of these parameters will be analysed, and, if required, corrections derived, before the first trial of the system as a multi-wavelength thermometer begins in Autumn 2013.

2.2 Emissivity measurements

A facility for measurement of emissivity was developed at CMI (see Figure 2). The facility consists of a spherical cavity in which a heated sample is placed. The heating element has a dimension of 13.5 cm x 13.5 cm. The cavity's outer surface is kept at ambient temperatures through water cooling (copper pipes in Figure 2).



Figure 2. Emissivity measurement facility at CMI.

The temperature of the sample is measured by contact and non-contact thermometry. For the contact measurement, a type N thermocouple is inserted into the sample. For the non-contact temperature measurement, two radiation thermometers (Heitronics TRTII and an LP5) operating at different wavelengths (8-14 μm ; 3.9 μm ; and 1.6 μm) are used to measure the heated sample through an aperture of 5 cm diameter. From the temperature difference between contact and noncontact thermometers, the emissivity of the material can be determined.

The initial system tests were performed with fire clay, whose literature value of emissivity is 0.91 at 70 °C. Its emissivity was determined at 100 °C (Table 1). Sample temperatures were determined with the thermocouple and the radiation thermometer (at 8 – 14 μm , with the emissivity set to 1.00). Based on these measurements the emissivity was estimated to be 0.89.

Table 1. Results of the emissivity measurement of the fire clay using the developed facility

Temperature TC "N"/°C	Temperature, $\epsilon = 1.00/^\circ\text{C}$	Calculated emissivity
111.46	98.76	0.89

2.3 Size-of-source effect (SSE) measurements

VSL has developed a characterization facility (Figure 3) for size-of-source determination which can simulate industrial conditions (e.g., with large background reflections, different ambient temperature conditions, etc) [5]. The facility has been characterized for the influence of the apertures and the different conditions of the background radiation emanating from the wall of the furnace.

In addition a scanning method for determining SSE, which was initially proposed by VSL, has been developed further [6]. The conventional methods used in radiation thermometry to determine SSE involve the use of a stable radiance source and several sets of circular apertures with different sizes and performing several sets of measurements. In the scanning method, a single slit is placed in front of a radiance source aperture. The radiation thermometer scans across the lateral width of this slit, and the SSE deduced from this measurement. The obvious advantage of this method is that it can be implemented automatically, thereby shortening the required measurement time. Further analysis of the method has shown that the results obtained are comparable with the results from the direct method.



Figure 3. Facility for size of source characterization developed at VSL.

2.4 Best measurement practice for cavity-based radiation thermometers

Cavity-based radiation thermometers (also known as metallic [or gold]-cup radiation thermometers) have been proved useful in industrial applications. These devices work by bringing a reflecting cup (often a hemisphere) close to the surface to be measured. Pseudo-blackbody radiation is established in the cup, negating the emissivity of the surface and so facilitating reliable temperature measurement. However, due to conditions in the field where the geometry of the surface under study is far from ideal, the accuracy of the results provided by this type of radiation thermometer is highly influenced by the surface geometry. Typical real examples are tubular and sloping surfaces such as those commonly encountered in petrochemical processing. VSL has built a facility (Figure 4) where cavity-based radiation thermometers can

be properly characterized with different surface geometries.

Initial results have shown that the uncertainty associated with the measurement on a curved surface at a temperature of 700 °C could be 3.5 °C ($k = 2$). This uncertainty attributed to the surface geometry is significantly high, more than half of the total uncertainty (6.1 °C) of the measurement. For sloping surfaces, an uncertainty contribution of the surface geometry amounts to 0.4 °C (at a maximum angle of 20 °), with the overall uncertainty of 5.4 °C.

These initial findings show that metallic cup thermometry is relatively insensitive to modestly sloped surfaces but could be strongly affected by curved surfaces. This is the subject of further investigation.

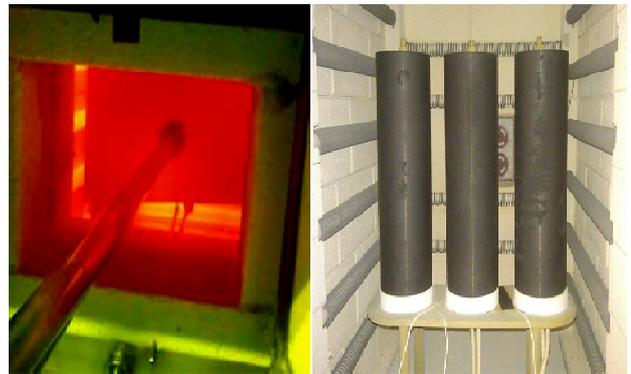


Figure 4. Characterization of cavity-based radiation thermometer on various source geometries.

3 WP2: Validated methodology for lifetime and drift tests for contact thermometry sensors (>1000 °C)

This WP aims at developing rigorous processes for determining the lifetime of base metal and the drift characteristics of base and noble metal thermocouples, firmly grounded in traceability to the SI (i.e. to the ITS-90). A EURAMET guide will be prepared on how to perform these tests in a rigorous way. Until now, these measurements were largely undertaken by manufacturers, often without reliable traceability. The results from testing different types of thermocouple will facilitate better understanding of the processes (e.g. chemical, physical) causing the drifts.



Figure 5: Experimental setup of the thermocouple drift and lifetime experiments at SMU

- 1-type K and N thermocouples (left side)
- 2-horizontal 3 zone furnace,
- 3-left side of the furnace chamber,
- 4- stabilization box with stable and monitored temperature for the thermocouple reference junction,
- 5-switch,
- 6-multimeter for measuring the output of thermocouple

A selection of base metal mineral insulated metal sheathed (MIMS) thermocouples (different sheathes and diameters) from different suppliers around Europe were collected and distributed to the partners. Drift tests were performed by UME, LNE-Cnam, SMU and CMI. For illustrative purposes the experimental set up for thermocouple tests at SMU is given in Figure 5.

The procedures for the life time and drift testing are given in outline form below.

3.1 Procedure for lifetime testing

New, untreated and uncalibrated thermocouples should be used for the lifetime testing. The following procedure was proposed for determining the lifetime of the thermocouples:

1. Prior to the measurement no heat treatment was to be performed, e.g. calibration or annealing
2. A good quality temperature reference standard (e.g. a Pt/Pd thermocouple) should be used to determine the temperature of the furnace.
3. Test of thermocouple sensors at the desired temperature. The testing temperature is that given in the supplier specification starting from the maximum allowable temperature for short term then adding +5 %.
4. Regular (continuous) measurement of the thermocouple output (with automatic or manual data logging). The actual temperature should be checked via the reference standard periodically (e.g. once per week).
5. The tests will be finished if
 - a. The thermocouple goes open circuit
 - b. The deviation of the tested thermocouple from standard EN IEC 60584 is three times higher than the specified tolerance.

3.2 Procedure for drift/stability testing

Two different procedures were developed for determining the drift in different temperature regimes (details are specified in Table 2 below):

- Short term use at elevated temperatures
- Long term continuous use at lower than top temperature specification

3.2.1 Drift determination: short term at elevated temperatures

The following procedure for determining thermocouple short term drift was developed:

1. Calibration of the tested thermocouple to the maximum temperature intended for use, including measurement of the homogeneity.
2. Test of thermocouple sensors at desired temperature. The testing temperature is that given in the supplier specification for the maximum allowable temperature for short term use.
3. The duration of the test is specified as 8 h (or shorter if the thermocouple fails)
4. Re-calibration of tested thermocouple at the maximum temperature intended for use.
5. Repeat point 3 and 4 three times.

Table 2: The testing temperatures for the evaluation of life time and drift/stability testing of thermocouples along with the thermocouple types

Institute/Company	Aging temperature for life-time test/°C	Aging temperature for base metal thermocouple drift (continuous) /°C	Aging temperature for base metal thermocouple drift (short-term) /°C	Aging temperature for noble thermocouple drift (continuous) /°C	Aging temperatures for noble metal thermocouple drift (short-term) /°C
Meggitt	-	1000 (K, N)	1100 (K,N)	1000 (R, S)	-
UME	1300 (K,N)	1000, 1100 (K, N)	1100, 1300 (K,N)	1000 (R, S)	1600 (R, S)
SMU	1300 (K,N)			1000 (R, S)	1600 (R, S)
LNE-Cnam	1300 (K,N)	1000, 1100 (K, N)		1000 (R, S)	1600 (R, S)
CMI	1300 (K,N)	1000, 1100 (K, N)	1100, 1300 (K,N)	1000 (R, S), 1600 (B)	1720 (R, S)

3.2.2 Drift determination: Long term continuous use

The following procedure for determining thermocouple long term drift under continuous use was developed:

1. Calibration of the tested thermocouple to the maximum temperature intended for use, including measurement of the homogeneity.
2. Test of thermocouple sensors at desired temperature. The testing temperature is that given in the supplier specification for the maximum allowable temperature for continuous operation.
3. The test duration is a minimum of 4 months.
4. Calibration of tested thermocouple at the maximum temperature intended for use every

week in the first month and every 2 weeks for the following months.

5. The tests will be finished if
 - a. The final time is reached
 - b. If the thermocouple goes open circuit
 - c. The deviation of the tested thermocouple from standard EN IEC 60584 will be three times higher than the desired tolerance.

These procedures are currently being refined through testing at the partner institutes. WP2 will culminate in on-site testing of thermocouples using the developed EURAMET guide at the industrial JRP-Partner (Meggit) and also at collaborator facilities.

4 WP3: Self-validating contact thermometry sensors for above 2000 °C

The aim of this WP is to develop reliable self-validating contact thermometry sensors and traceable measurement methods for the measurement of temperatures above 2000 °C in vacuum or inert atmospheres and up to 1800 °C in oxidizing atmospheres.

The first self-validation concept pursued is based on the use of miniature fixed points with defined and stable melting temperatures which are combined directly with commonly used thermocouples to detect their drift effects [8]. The second self-validation concept is based on the simultaneous use of a primary thermometry method to measure temperatures without drift effects. The approach followed in HiTeMS combines an electrical noise thermometer with a thermocouple, the former is then used to validate thermovoltage output of the thermocouples [9].

Compatibility studies of materials usable for the construction of high-temperature miniature fixed points stable at temperatures around 2000 °C were performed. As a result two miniature fixed-point cells (Pt-C, 1738 °C and Ru-C, 1953 °C) usable with MIMS thermocouples in inert atmospheres will be evaluated at NPL.

Four miniature fixed-point cells of two different designs usable in oxidizing atmospheres have been constructed by PTB using pure palladium (1553.4 °C) and pure platinum (1769 °C) as fixed-point materials. At LNE-Cnam, four innovative modules have been assembled with pure palladium and pure platinum. An evaluation program for the detection and analysis of the phase transitions has been developed by PTB.

Furthermore, PTB and unfunded partner Endress+Hauser have developed combined thermocouple-noise temperature sensors. These consist of two type S thermocouples or two type B thermocouples and a noise resistor, respectively. The accuracy of these devices has been tested at the freezing points of copper and silver. The mean noise temperatures measured agree to the well-known fixed-point temperatures (ITS-90) within 0.4 K at the freezing point of copper and within 0.2 K at the freezing point of silver. Further measurements at higher temperatures demonstrate the suitability of such combined sensors to detect possible

drift effects of the thermocouple output. As an example the temperature output of two thermocouples and the resistance of a noise sensor versus time of a combined sensor are presented in Figure 6. The two curves are closely matched. It should be mentioned that provided a suitable noise sensor material is selected the value of the noise sensor resistance also gives an indication of possible instabilities in the thermocouples.

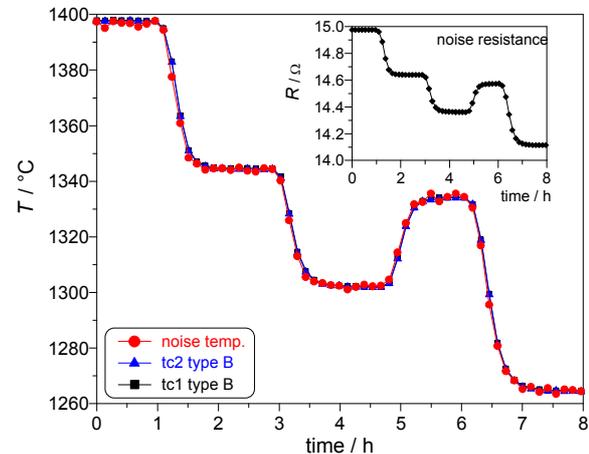


Figure 6: Temperature course of a type B based combined thermocouple-noise temperature sensor

The melting curves measured by using the thermocouples with integrated miniature fixed points allow a unambiguous assignment of the corresponding melting temperatures provided that agreed methods for analysis of the curves are used, for instance the application of regression lines. The measurement uncertainties of the melting temperatures are of order 1-2 K at the melting points of palladium and platinum which corresponds to the detectable limits of drift effects of the thermocouples. Similar detection limits are attainable by using noise thermometry as an independent method if sufficient time is allowed for measurement.

5 WP4: Validated methods for non-contact thermometry above 2500 °C including novel correcting techniques

In this WP, the main objective is to apply *in-situ* recalibration techniques in industrial type installations for non-contact thermometry. The two issues being addressed are that of viewing window contamination and thermometer drift. Two different applications have been identified; at the Severe Accident Mastery Laboratory (LMA) of CEA Cadarache for the studies of the reactions of corium, and at GDF-Suez in the installations devoted to the study of prototype industrial glass forming furnaces. These two unfunded partners are contributing to the completion of some of the deliverables of the project and allowing use of their installations for the *in-situ* tests.

The first step of this work was the realization of rugged small-size high-temperature fixed points (HTFP) [10] to act as *in-situ* calibration devices in inert atmospheres but which were also stable and robust, even

in hostile environments. The cells, constructed in graphite, were adapted to the use in the CEA/LMA facilities. Their design was based on the LNE-Cnam hybrid cell design and were filled using the piston method developed by LNE-Cnam [11]. The crucible walls were thicker than in the usual design in order to improve the robustness whereas the length of the cells was reduced so that the temperature distribution effect would be minimized.

Figure 7 shows a schematic view of the cell. Three different HTFPs were realized for this study. Several cells at the fixed-points of Co-C (1324 °C), Ru-C (1954 °C) and Re-C (2474 °C) were constructed in the three NMIs, LNE-Cnam, UME and NPL. At the end of the filling process, the cells were run for several days in each of the NMIs to assess the metrological characteristics of the melt and freeze plateaus. In most cases, the repeatability of the melting temperatures and the melting ranges were considered larger than the ones obtained with the conventional design of cells. This is however understandable due to the small dimensions of the cell, the small amount of metal and the lower purity level of the metals used for the filling of the cells. However for industrial applications the performance was more than adequate.

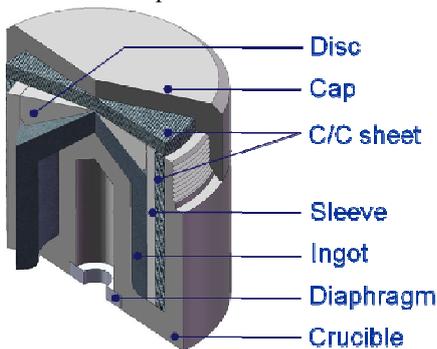


Figure 7. Schematic view of the rugged HiTeMS HTFP cell. Dimensions are 24 mm length, 24 mm diameter and cavity dimensions of 5 mm diameter and 15 mm length (emissivity of 0.996, reaching 0.999 with the 3-mm added aperture).

The measurements performed at CEA/LMA with these cells have allowed the assessment of their unique capabilities to withstand large heating and cooling rates and still exhibit good repeatability well within the expectations (namely 1 K at approximately 2700 K). For example Figure 8 shows a typical melt and freeze cycle of a robust Co-C cell of the design shown in Figure 7.

This cell has undergone 4 melt and freeze cycles performed in a high temperature furnace with setpoints of ± 400 °C around the melting temperature. These setpoints led to very rapid heating typical of what is encountered in industry, nevertheless the cell was undamaged demonstrating robustness. Further details of results obtained so far can be found in [12-13].

The effect of window transmission on the measured temperatures was studied and an algorithm was developed to help correct for this effect by the use of HTFPs [14].

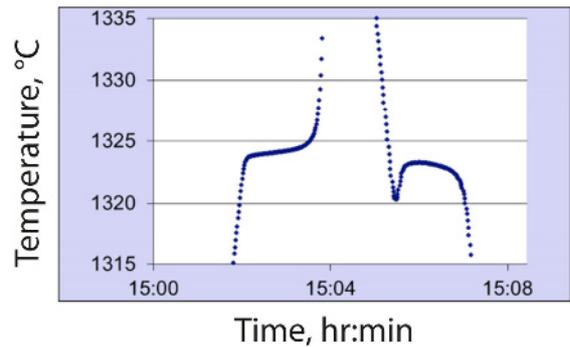


Figure 8: x-axis time, y-axis temperature in °C. Performance of a robust Co-C of design shown in Figure 7. Plateau duration ~1 minute. Melting range ~0.350 °C

6 WP5: Traceable temperature measurements for exotic thermal processing methods

This WP addresses traceable temperature measurement in a specific exotic thermal processing method: that of laser heat treatment of metal surfaces.

Over the last 15 years laser surface heat treatment for steel or cast iron parts has been established in industrial mass production, e.g. automotive or aerospace industries [15]. Precise temperature measurement and control is essential to ensure reproducible quality of the parts. For successful heat treatment the process temperature needs to be controlled within a band of only a few kelvin, temperatures too high can cause melting of the parts surface and temperatures too low result in lower surface hardness and smaller heat penetration depth.

The temperature in laser hardening processes is measured by radiation thermometers developed specifically for this application. The thermometer is closely integrated into the laser head, partly using the same optical system, optimized to effectively block the laser radiation from entering the radiation thermometer and parasitic stray light. A fast response time is required to ensure reliable control of the laser heating process. Due to the mechanical and electrical integration into complex and large machine systems, and also because of the sensor drift due to wear and contamination of the optical components, *in-situ* methods for calibrating the integrated radiation thermometer are required.

For this reason a mobile induction heated fixed-point device for fast calibration in the temperature range from 1000 to 1500 °C was developed by PTB and FhG in the context of WP5. In a first step different variants of temperature measurement configurations were investigated, typically used in industrial laser heat treatment, to define the requirements for the device and to analyse the status of currently achievable measurement uncertainties.

The geometry and arrangement of system components and the processing parameters of the induction heated fixed-point device were then optimized by a computer simulation with FEM (finite element method) and FDM (finite difference method). By way of example Figure 9 shows the influence of induction

frequency on the temperature uniformity of the fixed-point cell.

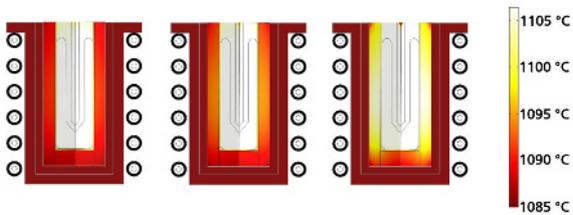


Figure 9: FEM simulation of temperature field across a fixed-point cell after induction heating (variation of induction frequency: left: 125 kHz, middle: 250 kHz, right: 1000 kHz)

Based on the results of the modelling a prototype induction heated fixed-point device was constructed at PTB. The device has a water cooled and vacuum-sealed housing which can be evacuated, purged with inert gas with copper tubes forming the induction coil (Figure 10).



Figure 10: Induction heated fixed-point device, inner components with top cover removed (induction coil with ceramic cell holder, graphite fixed-point cell and graphite felt insulation)

For safety reasons all important system parameters like shielding gas flow, water flow and temperature and residual oxygen content are measured. Cu (1085 °C), Fe-C (1154 °C) and Co-C fixed point cells with a 3 mm and a 5 mm aperture, respectively, were manufactured and investigated with respect to reproducibility. Figure 11 shows the Fe-C repeatability as measured on two consecutive days.

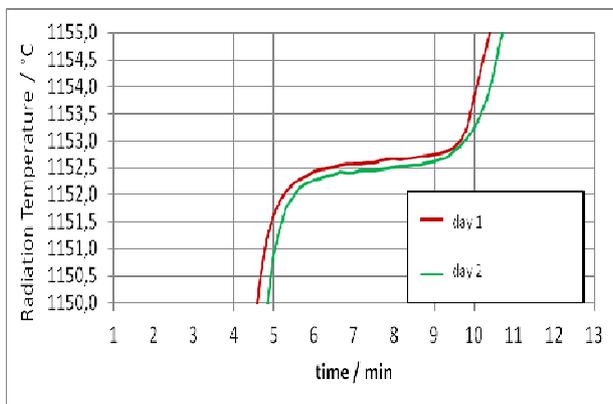


Figure 11: Melting plateaus of a Fe-C fixed-point cell installed in mobile induction heated fixed-point device.

In the next stage of the project the fixed-point will be tested at an industrial site and additionally the

emissivity of steel and cast iron in the temperature range between 800 °C and 1400 °C will be investigated and measured. The combination of precise and reproducible radiation thermometry with sound emissivity corrections will reduce the uncertainty of the thermal processing temperature measurement and introduce robust traceability into the measurement chain.

7 WP6: Establishment of reference functions for non standard thermocouples

The purpose of this WP is to develop a distributed capability within the EU for the determination of metrological quality low uncertainty reference functions of non-standard high temperature thermocouples. For reference functions to be widely acceptable measurements must be performed by more than one institute and preferably by more than one method. To demonstrate the established capability, the reference function of a non-standard thermocouple type is to be determined. Participants of the WP are NPL, CEM, LNE-Cnam, and SMU. NPL and LNE-Cnam intend to calibrate the thermocouples with HTFPs, while CEM and SMU intend to perform comparisons against a blackbody. Through comparing the reference function determined by both approaches the lowest uncertainty can be attained.

NPL and LNE-Cnam have constructed a series of high temperature fixed points (HTFPs) Pt-C (1738 °C), Cr₇C₃-Cr₃C₂ (1742 °C), and Ru-C (1954 °C). Due to the high price of the ingot materials, miniature HTFP cells are used. NPL and LNE-Cnam constructed their HTFP cells with different, independent designs. The immersion characteristics and other performance aspects of the fixed point cells listed above are currently being assessed. The melting temperature of the Ru-C cells (for thermocouple calibrations) is being determined using radiation thermometry at both NPL and LNE-Cnam, and the two results will be compared. The suitability of the cells for calibration of W-Re and Rh-Ir thermocouples will be evaluated.

CEM has already established its capability for calibrating thermocouples by a blackbody comparator [16], SMU are currently implementing their system. The principle is the same. The thermocouples whose reference function is being determined are placed in a blackbody comparator. The temperature of the blackbody is determined in terms of ITS-90 through using a radiation thermometer. The thermovoltage of the thermocouple is determined at that temperature and hence a temperature calibration point is determined. This is repeated for a number of temperatures and the reference function is established.

Initially, Ir-60%Rh / Ir thermocouples were selected as the subjects of the reference function determination, because they can be used in oxidising atmospheres to approximately 2000 °C. Reference functions, but with high uncertainties, have been published for various Rh-Ir thermocouples [17, 18]. Although Rh-Ir thermoelements exhibit high resistance to oxidising environments, they must be protected from the graphite crucibles when used

with fixed point cells. No closed ceramic tubes are available for use to 2000 °C, so a metal sheath (Ta) had to be used. This tube must itself be protected from oxidation so the volume inside the tube (containing the thermocouple) contains argon gas which is hermetically sealed into the unit. Construction of the Rh-Ir thermocouples was performed in collaboration with Omega Engineering Ltd., following the same construction methodology as that employed for commercially available W-Re thermocouples. Figure 12 shows some preliminary results with the thermocouples at NPL using the fixed points of Pt-C and Ru-C. It is clear that problems were experienced with the assembled devices when used at temperatures around and above 1900 °C, apparently due to the interactions between Ir vapour and the protective Ta sheath which caused severe damage to the sheath exposing the thermoelements inside.

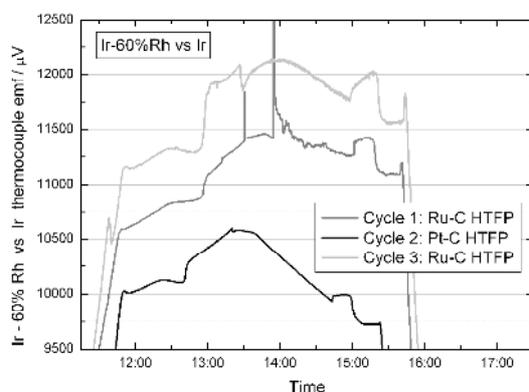


Figure 12: Plot of melting and freezing curves of Pt-C and Ru-C HTFPs measured using the Rh-Ir thermocouple, illustrating the high performance of the cells (as exemplified by the clear, high quality melting and freezing plateaus) and the poor performance of the thermocouples (as exemplified by the erratic emf drift).

As a result of these problems, the Rh-Ir thermocouples were replaced with Pt-40%Rh / Pt-20%Rh thermocouples, and the upper temperature range restricted to 1750 °C. Four thermocouples were constructed by NPL and are currently being circulating between NPL, CEM, LNE-Cnam, and SMU. When the measurements are complete the results will be compiled to produce a reference function, thereby demonstrating the establishment of the distributed capability.

8 Summary

This paper provides a summary of the progress made in the EMRP project HiTeMS. Long standing issues regarding the measurement of both contact and non-contact thermometry at high temperatures are being addressed through the broad range of research that is being performed. Through pooling of resources and expertise, as well as genuine collaboration between national measurement institutes and industry, important advances are being made in addressing long standing temperature measurement problems.

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