Improved temperature measurement for improved processes

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With thanks to: Klaus Anhalt (PTB), Frank Edler (PTB), Jon Pearce (NPL), Mohamed Sadli (CNAM), Radek Strnad (CMI), Edger Moreno Vuelban (VSL)

Outline of talk

- Outputs of EMRP project HiTeMS: High temperature metrology for industrial applications >1000 °C
- Introduction to project
- Summary of some of the technical achievements
  - Both in non-contact and contact thermometry
  - Illustrations of applications given
- Summary

HiTeMS: Introduction

- Solving industrial high temperature thermometry (>1000 ºC) problems
- Non-contact thermometry

  Emissivity, reflected radiation, variable transmission
- Contact thermometry

  Thermocouple lifetime/drift, *in-situ* validation, reference functions of exotic thermocouples
- Three year European Metrology Research Programme project from Sep 11 – Aug 14
- Why improve temperature measurement in industry?

HiTeMS: Introduction

- Improved product quality, optimise energy use, reduced carbon emissions, zero waste manufacture
- Typical sectors impacted: e.g. aerospace/space (~1300 – 3000 °C), nuclear fuel and essential nuclear safety testing (~1800->2500 °C), refractory metals (2500+ °C), silicon carbide, carbon/carbon composites (to >2800 °C) and iron, steel, glass and ceramics (1100 to 2000 °C).

HITEMS PARTNERS (14) + REGS (2)

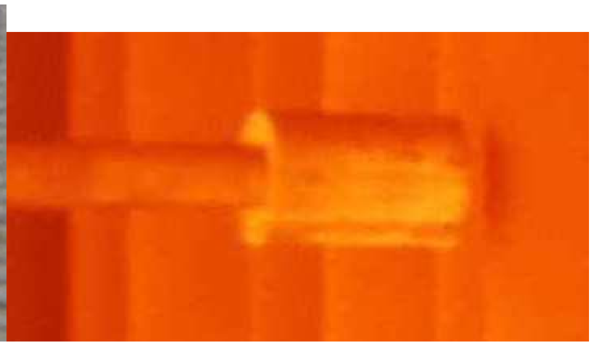
5

Traceable and accurate measurement techniques for *in-situ* surface temperature >1000 °C

- Participants: **VSL**, CMI, INRIM, SMU
- Target – to reduce the uncertainties in industrial radiation thermometry *and* establish measurement traceability
- Technical challenges addressed:

  Reflected radiation

  Unknown emissivity



Traceable and accurate measurement techniques for *in-situ* surface temperature >1000 °C

- Place known traceable temperature points in the measurement field to correct for unknown emissivity and reflected radiation
- Three approaches:

  Ultra-violet multi-wavelength

  Thermometry (down to 350 nm)

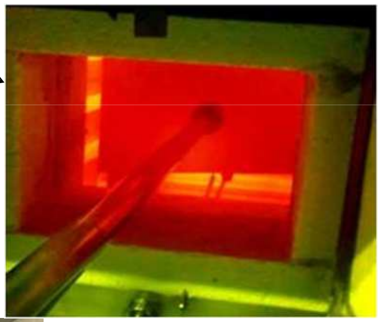
  Traceable gold cup pyrometry

  Active two colour thermometry

Traceable and accurate measurement techniques for *in-situ* surface temperature >1000 °C

- Facility for assessing how the output of a gold cup pyrometer is affected by:

- sloping surfaces



- curved surfaces

Traceable and accurate measurement techniques for *in-situ* surface temperature >1000 °C

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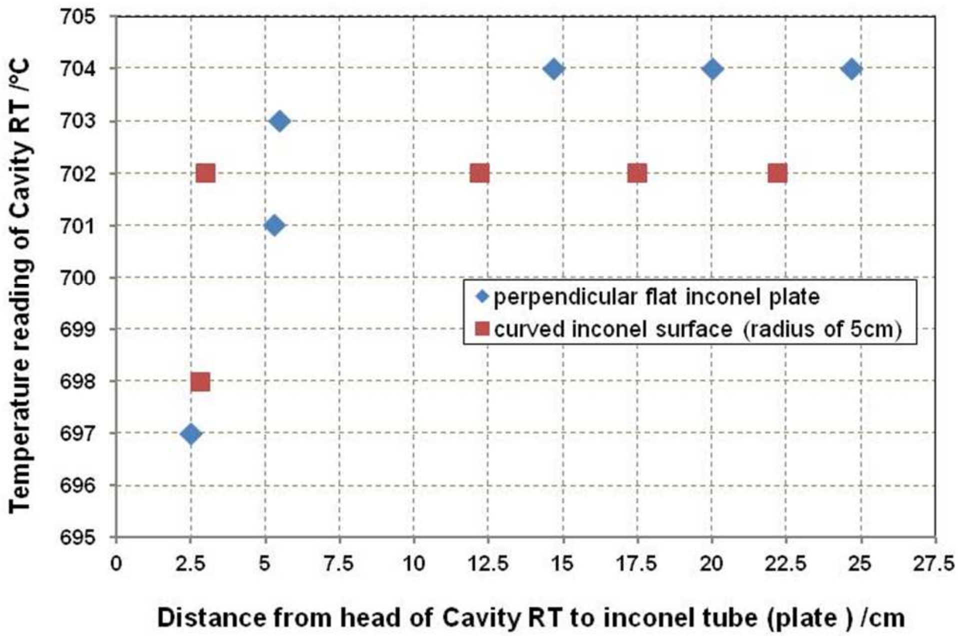
The effect curved surfaces is significant – loss of radiation from target and increased leakage of radiation into the measurement area from the high ambient background



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Validated methodology for lifetime and drift tests for contact thermometry sensors above 1000 °C

- Participants: **CMI**, CNAM, LNE, NPL, SMU, TUBITAK UME, MSS
- Objective: To establish a rigorous and standardised way of determining the lifetime and drift characteristics of base and noble metal thermocouples
  - Method established
  - Euramet guide prepared
  - Drift and lifetime tests performed with temperature and thermocouple diameter

Validated methodology for lifetime and drift tests for contact thermometry sensors above 1000 °C

Lifetime of base metal thermocouples (N/K) to 1300 °C

Drift testing of base metal (N/K)

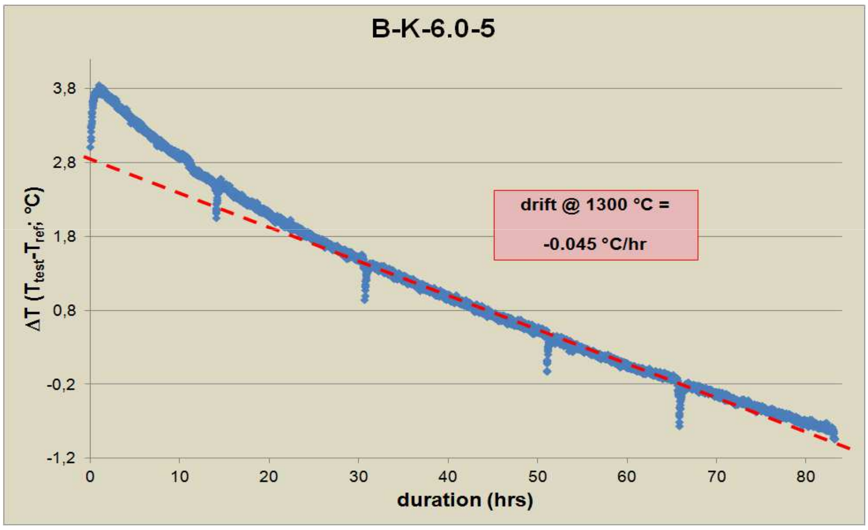
- 1000 °C & 1100 °C for continuous use
- 1100 °C & 1300 °C for short term use

Drift testing of noble metal (S/R/B)

- 1000 °C & 1720 °C for continuous use
- 1600 °C & 1820 °C for short term use

Lifetime tests of type K/N at 1300 °C after 6 hours

Typical drift of type K thermocouple with time exposure



Results indicate it might be possible to derive a correction for thermocouple drift – **in service** – extending useful sensor life (more work required to prove this)

Typical drift rate of type K thermocouple with diameter

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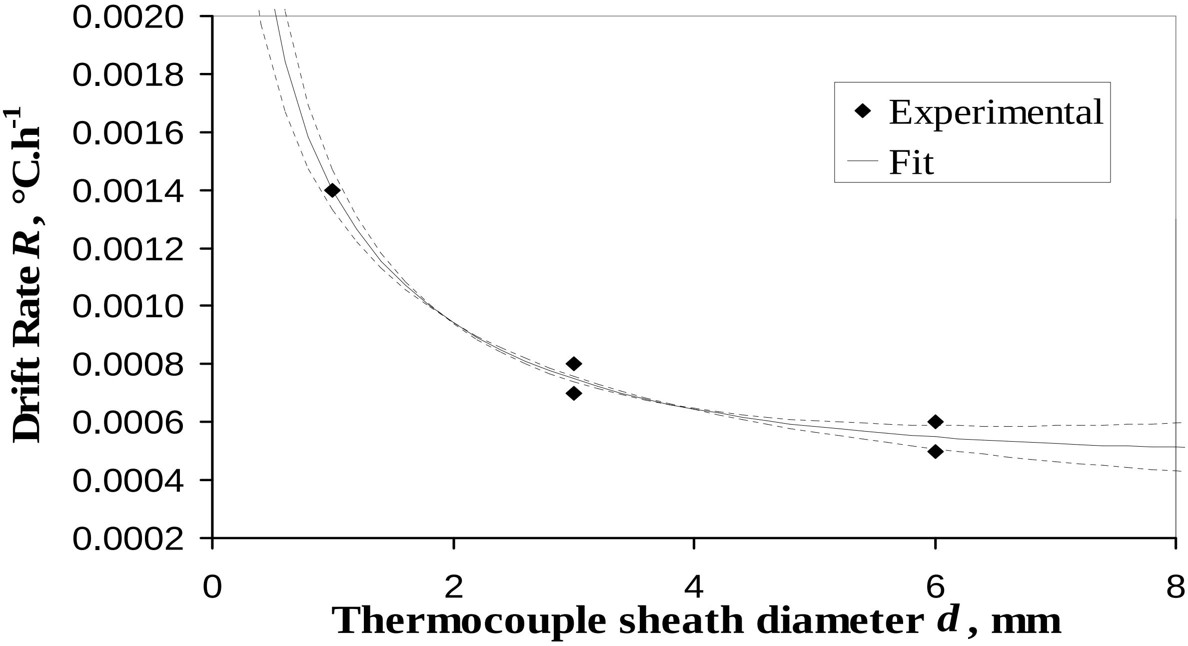

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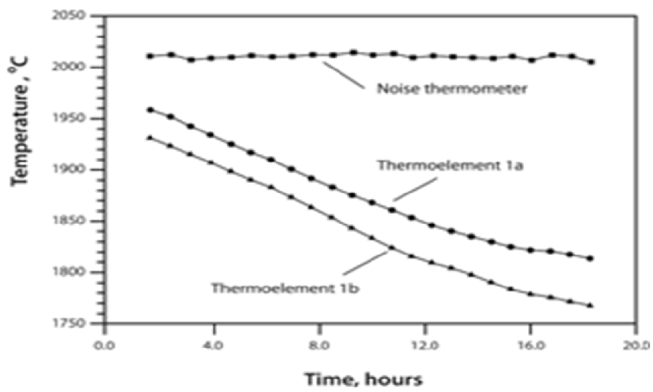
Self validating contact thermometry sensors for above 2000 ºC

- Participants: **PTB**, CNAM, E+H, LNE, NPL
- Objective: To develop *in-situ* self-validating contact thermometry sensors for temperatures to:
- >2000 °C in vacuum/inert atmospheres
- ~1800 °C in oxidising atmospheres

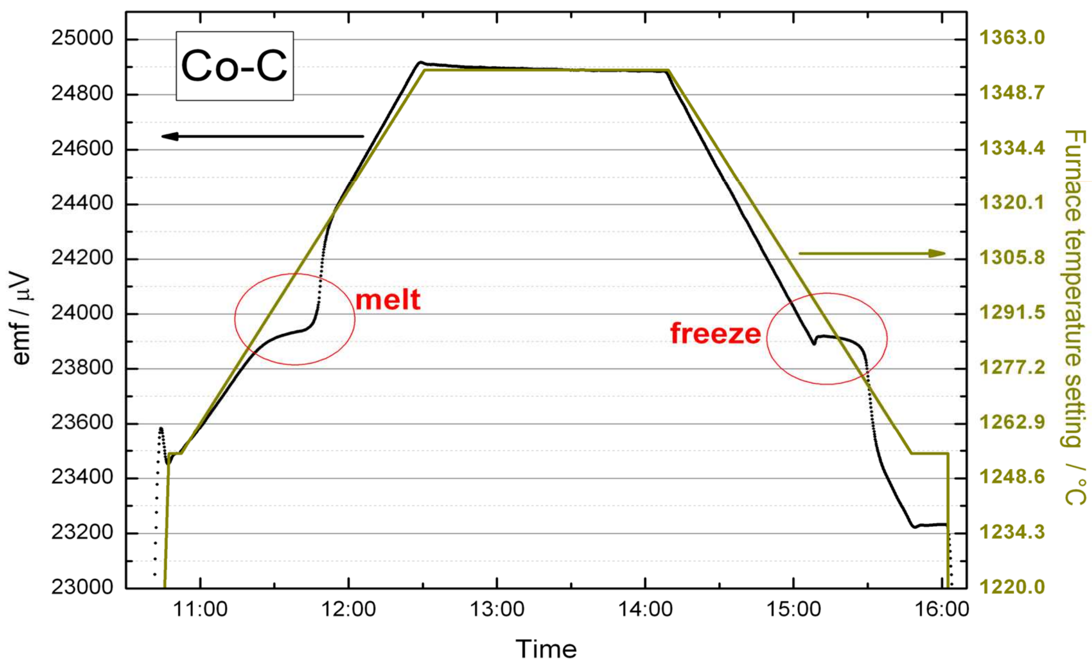


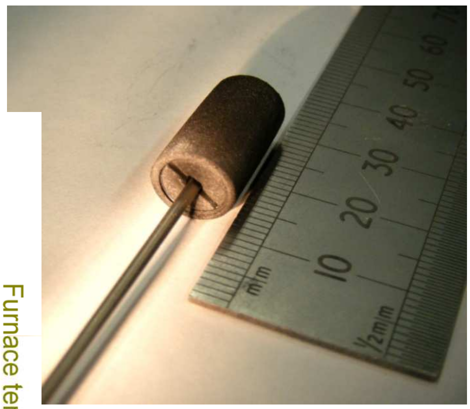
Self validating contact thermometry sensors for above 2000 °C

- Material compatibility study –sheaths /insulators/ thermoelements
- Novel mini-high temperature fixed points integrated with metal (eg Ta) sheathed thermocouples
- Allows *in-situ* calibration without sensor removal – essential as W/Re types become brittle (removal for recalibration not possible) and can drift >>50 °C

Self validating contact thermometry sensors for above 2000 °C

NPL approach





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

- Participants:**CNAM**, NPL, TUBITAK UME, CEA, GDF
- Objective: Develop *in-situ* methods for correcting non-contact thermometers viewing through contaminating windows or variable transmission paths eg fibre-optic
- High temperature fixed point blackbody sources used as stable references – *in-process*
- Typical fixed points were Re-C (2474 °C), Ru-C (1953 °C), Co-C (1324 °C)

Validated methods for non-contact thermometry >2500 °C including novel correcting techniques

- Example: nuclear safety experiments with corium at CEA
- Penetration rate of corium through concrete critically dependent on its temperature
- Corium temperature determined by radiation thermometry through progressively contaminating window
- Radiation thermometer views known high temperature fixed point blackbody *in-situ* – through window
- Use this to determine and correct for window transmission $L(\lambda, T) = L(\lambda, T_m)/\tau(\lambda)$

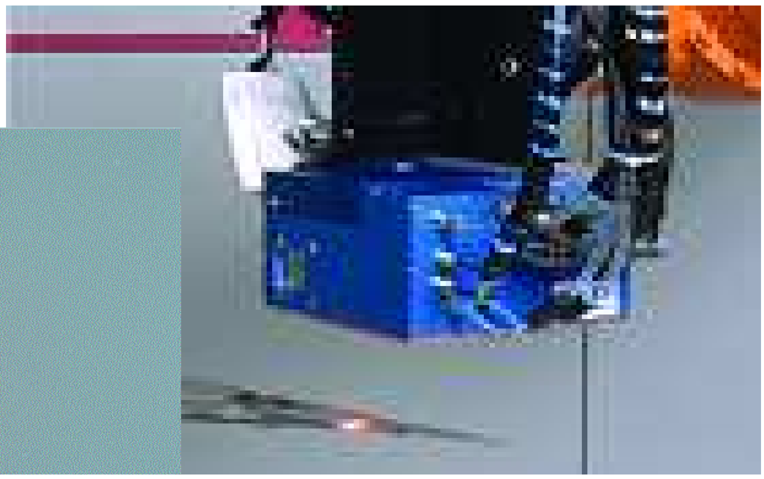
Corium experiments at CEA

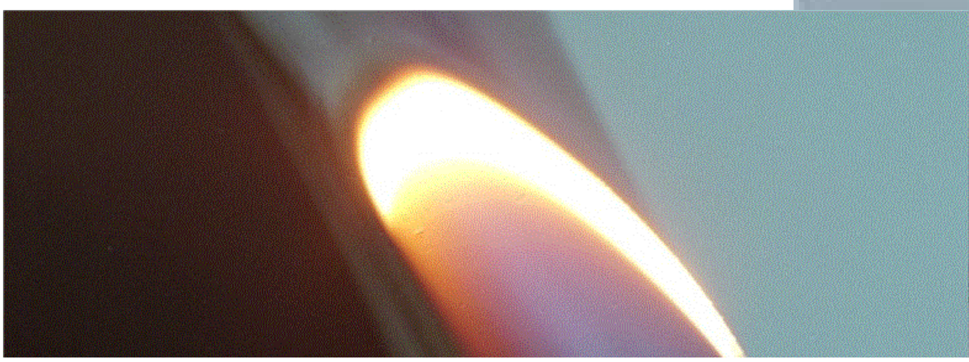
Traceable temperature measurements for exotic thermal processing

- Participants: **PTB**, SMU, REG(FhG)
- FhG – Fraunhofer Institute in Dresden – Institute for Material and Beam Technology
- Objective: Reliable and traceable non-contact thermometry in thermal processing with lasers
  - *In-situ* transmission corrections (full industrial use of WP4)
  - Emissivity – database for materials (eg turbine blades) that are processed by lasers

Traceable temperature measurements for exotic thermal processing

- Laser hardening
  - High powered laser – progressively scans across component – heating thin surface layer, producing a hard wear resistant surface



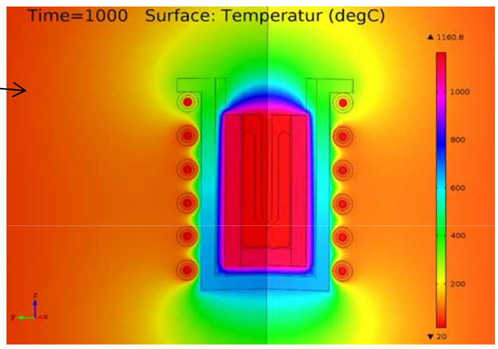


Traceable temperature measurements for exotic thermal processing

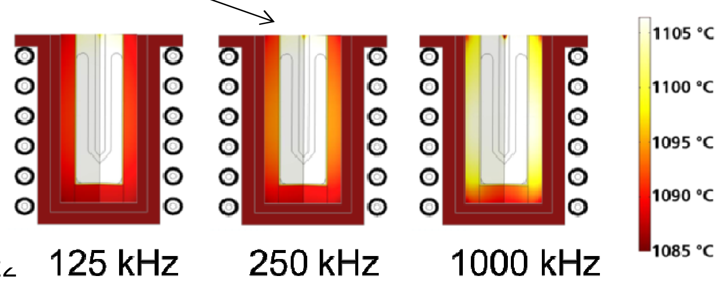
- Development of suitable high temperature fixed point plus induction heating device – correct for unknown transmission of window and optical fibre – to be used *in-process*
- Emissivity measurements corroborated by SMU
- Aim is to achieve reliable <u>and</u> traceable temperature measurement - vital for reliable control of laser hardening process

Traceable temperature measurements for exotic thermal processing

Modelling of the induction furnace, coil and fixed point response to induction frequency to optimise design



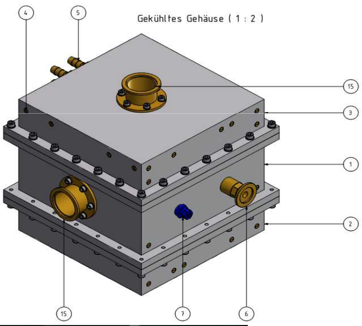
Courtesy of Marko Seifert - FhG

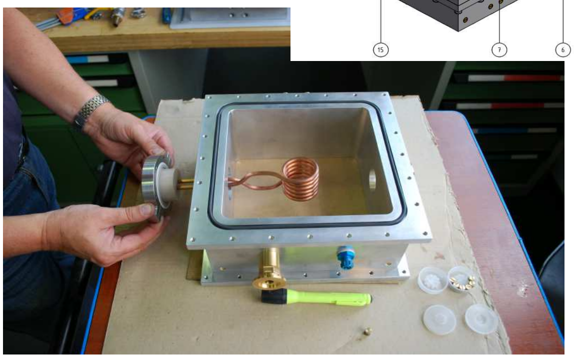


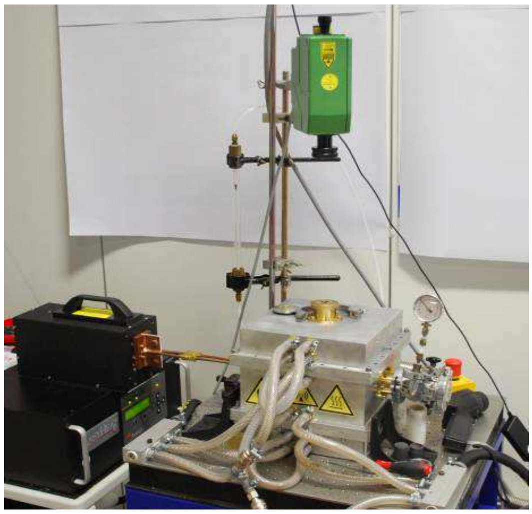
Inductively heated fixed point radiator

Fixed points of Cu, Fe-C and Co-C constructed 3 and 5 mm apertures

- Inner dimensions 200 mm x 200 mm x 200 mm
- Water-cooled
- Can be evacuated
- Can be purged with Ar, N2,…
- Can be extended to change top or bottom flange







Establishment of reference functions of non-standard thermocouples

- Participants: **NPL**, CEM, CNAM, LNE, SMU
- Objective: To establish EU capability for the determination of metrological quality low uncertainty reference functions for non-standard high temperature thermocouples
- Provide access to industry to wider range of reliable temperature sensors to improve process control

Establishment of reference functions of non-standard thermocouples

- Sensor used Pt/40%Rh-Pt/20%Rh thermocouple
- Insulator alumina, maximum temperature ~1800 °C
- Two groups of thermocouples constructed and measured in two phases
- Compare with published reference function ASTM E1751-09

Establishment of reference functions of non-standard thermocouples

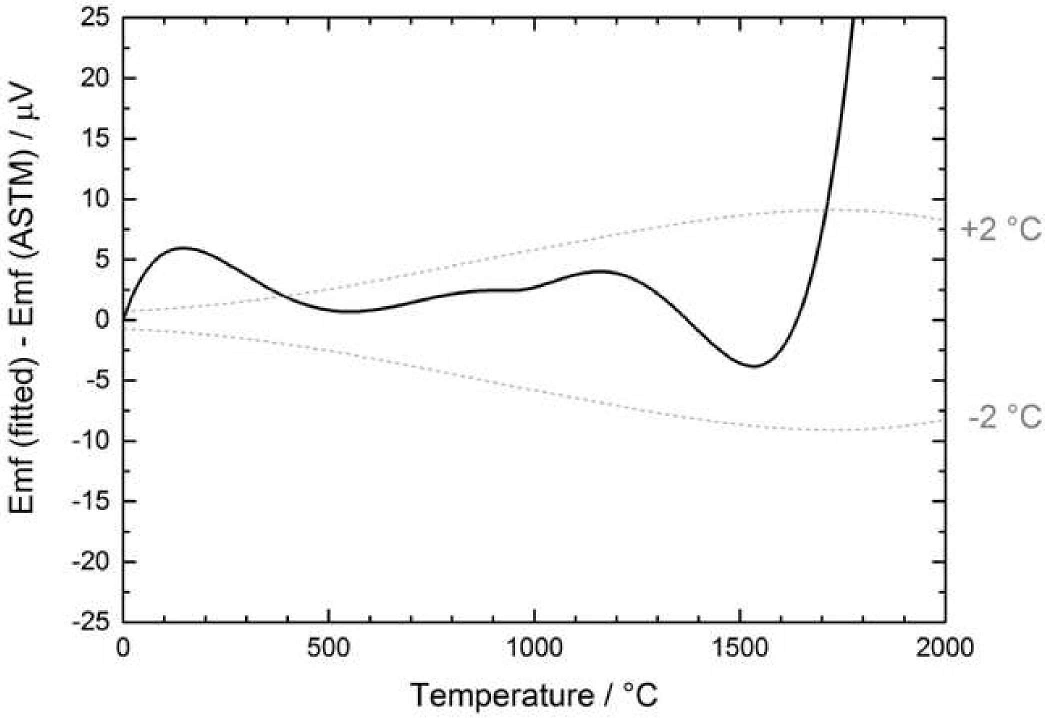
- The thermocouples were calibrated using the following capabilities

  NPL used fixed points of Sn, Zn, Al, Ag as well as HTFPs Co-C and Pd-C and Pt wire bridge

  LNE-CNAM used wire bridge Au, Pd, Pt

  CEM and SMU used radiation thermometer comparators
- Data was pooled and compared with the ASTM standard, a large deviation above 1500 °C was found because a wrong temperature for the Pt point was used by earlier researchers
- Distributed facility within EU established for low uncertainty reference function determination

Establishment of reference functions of non-standard thermocouples



Summary of HiTeMS – progress in solving...

- Non-contact thermometry problems

  Emissivity, reflected radiation, variable transmission
- Contact thermometry problems

  Thermocouple lifetime/drift, *in-situ* validation, reference functions of exotic thermocouples
- Two industry focused workshops to disseminate results
- Follow on project – looking at solving a number of specific temperature measurement problems in high value manufacturing – EMPRESS