National Physical Laboratory

Traceable thermometry for high value manufacturing: some case studies

Jonathan Pearce

Øg effektiviteten i din produktion

- temperaturmåling i industrielle processer

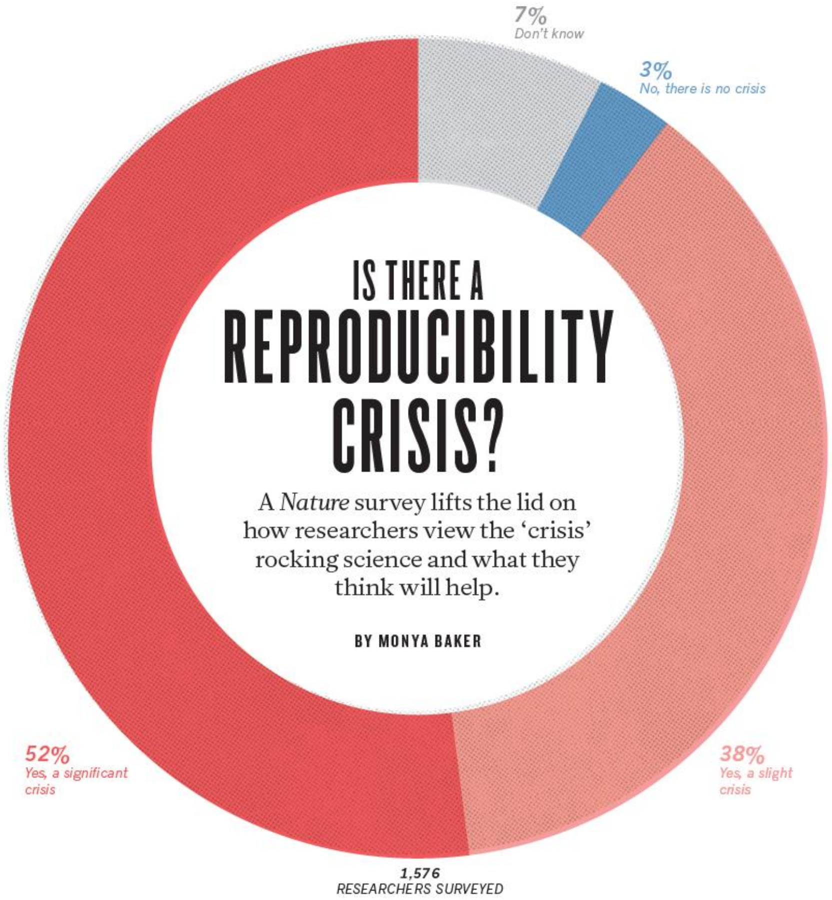
Teknologisk Institut, Aarhus den 10. oktober 2019

Introduction

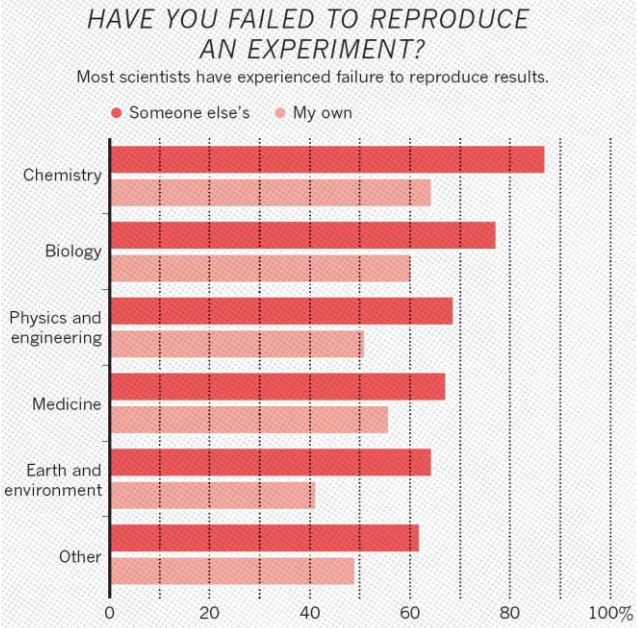
National Physical Laboratory

- Better efficiency implies better temperature control
- Better stability, lower uncertainty
- Traceability to the SI

- EMPRESS 2
  - Phosphor thermometry
  - Thermocouples
  - Combustion/flame thermometry
  - Fibre-optic thermometry
- Practical Johnson noise thermometry



Nature Vol. 533 26 May 2016 p. 452



COMMENT

CLIMATE Al Gore's second film joins distant dots in our warming world **p.400**

ECONOMICS *Das Kapital* reappraised for these tumultuous times **p.401**

REPRODUCIBILITY Enforce deposition and sharing of research materials **p.403**

CONSERVATION The many ways to judge a species' value to an ecosystem **p.403**

COURTESY OF UK NATIONAL PHYSICAL LABORATORY

Ground-based measurements of light bouncing off deserts can be used to calibrate satellite observations of reflectivity and improve climate modelling.

Metrology is key to reproducing results

Scientists of all stripes must work with measurement experts so that studies can be compared, urge **Martyn Sené**, **Ian Gilmore** and **Jan-Theodoor Janssen**.

Imagine you are a policymaker who needs to know how much carbon is stored in the South American forest. On-the-ground data in this area are slim. So when you come across two recently published maps of surface biomass, both made using the exact same satellite data, you think it's your lucky day. Unfortunately, these maps differ in their estimates of biomass by about 20% across the continent, and by even more on a local level. Which map, if either, can you trust[1]?

Many column inches have been dedicated to discussing this 'reproducibility crisis' in scientific research. Researchers are rarely incentivized to try to replicate results, and when they do, those results often don't match[2].

Little attention has been paid in these discussions to how metrology can help. Metrology is the science of measurement: practitioners develop internationally agreed reference points so that measures — of anything from length or mass to radiation ▶

27 JULY 2017 | VOL 547 | NATURE | 397

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Nature Vol. 547 27 July 2017 p. 397

Introduction

We can only answer questions like this if we can trace the measurement back to universal reference standards

In the case of temperature, this means traceability to the SI unit, the kelvin

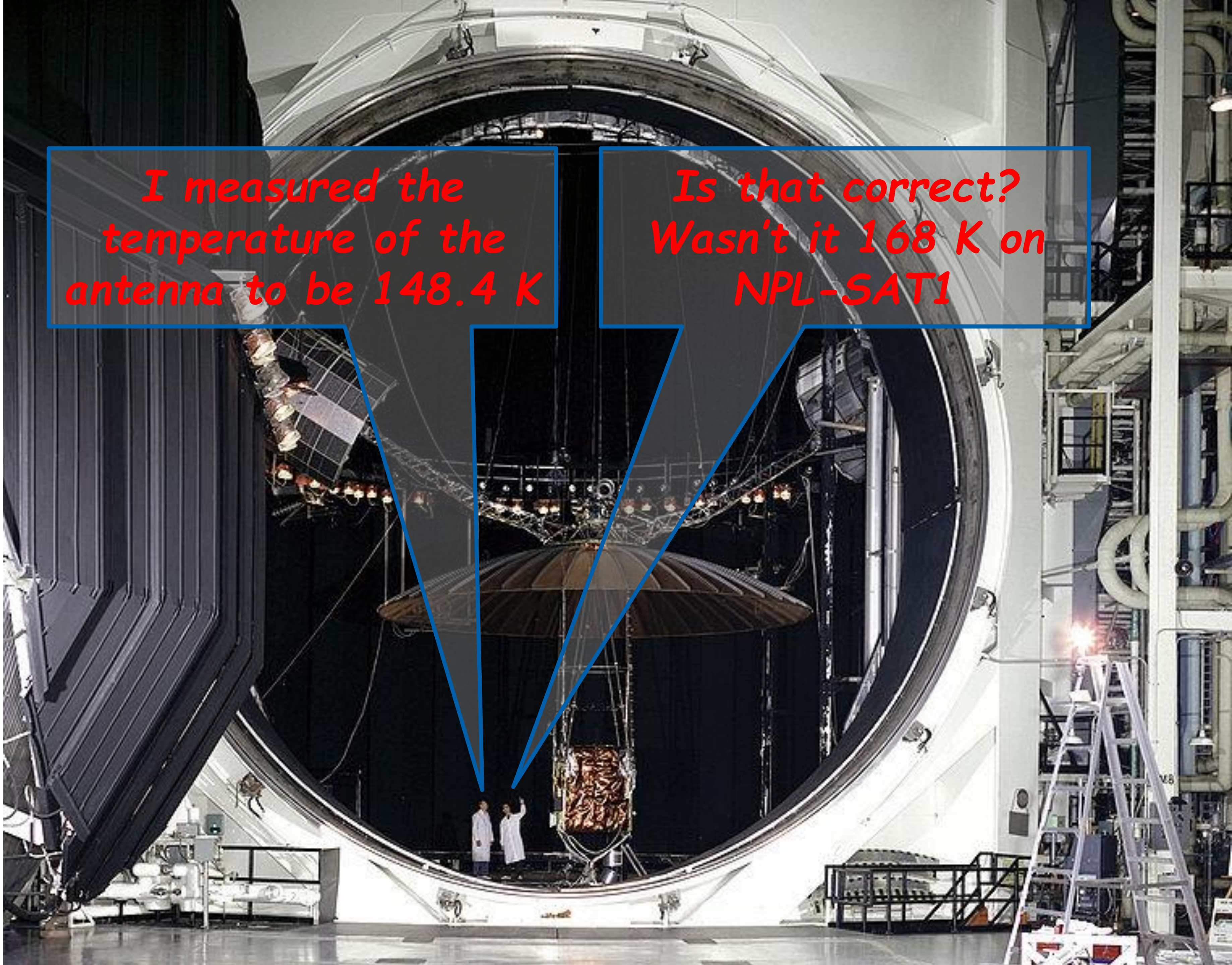

Image: NASA

National Physical Laboratory

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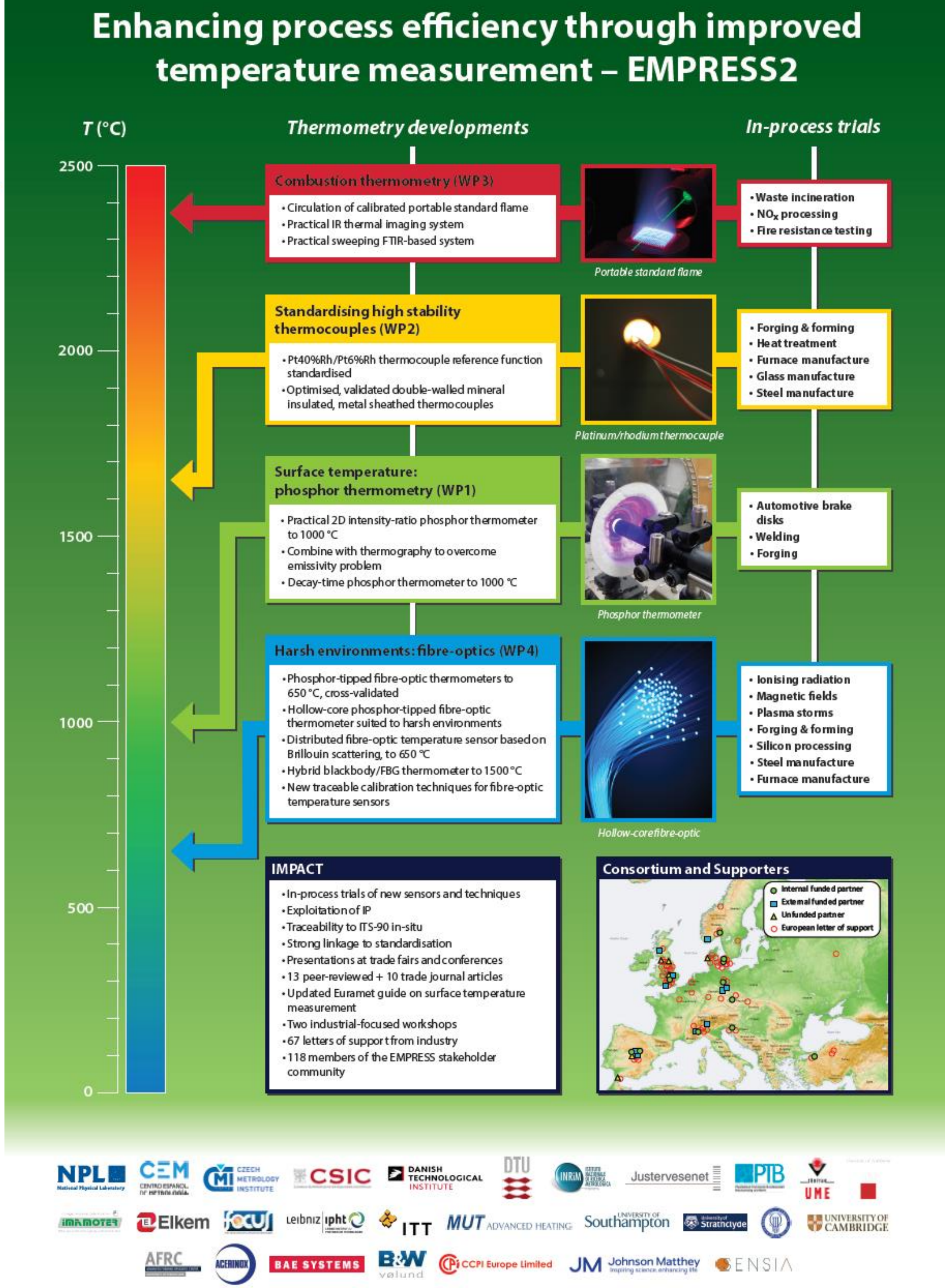
  - Fibre-optic thermometry
- Practical Johnson noise thermometry

EMPRESS 2

EMPRESS 2
TEMPERATURE METROLOGY FOR PROCESS EFFICIENCY

- Solve a suite of specific, documented process control problems in high value manufacturing
- By establishing *in-process* traceability to ITS-90
- WP1: Surface temperature: phosphor thermometry (STRATH)
  Extend to 2D
  Extend to 1000 ºC
  Combine with thermal imaging
- WP2: Standardising high stability thermocouples (PTB)
  Towards standardising Pt-40%Rh vs. Pt-6%Rh
- WP3: Combustion thermometry (DTU)
  Demonstrating its use in-process
- WP4: Harsh environments: fibre-optics (NPL)
  Completely new – introducing traceability
- WP5: Impact (AFRC)



NPL National Physical Laboratory

IO CSIC Consejo Superior de Investigaciones Científicas

Justervesenet

Danish Technological Institute

Univerza v Ljubljani

TÜBİTAK

PTB Physikalisch-Technische Bundesanstalt Braunschweig und Berlin

CEM Centro Español de Metrología

INRiM Istituto Nazionale di Ricerca Metrologica

DTU

CMI Czech Metrology Institute

University of Southampton

University of Cambridge

Universidad Carlos III de Madrid

IMAMOTER Istituto per le Macchine Agricole e Movimento Terra Consiglio Nazionale delle Ricerche

ITT Engineered for Life

University of Strathclyde

MUT Advanced Heating

Elkem

Leibniz ipht Leibniz-Institut für Photonische Technologien

AFRC Advanced Forming Research Centre University of Strathclyde

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BAE SYSTEMS

JM Johnson Matthey Inspiring science, enhancing life

B&W vølund

Acerinox

SENSIA

CCPI Europe Limited

Activity & specialism groupings

Phosphor thermometry (decay-time)

- INRiM – Phosphor thermometry development
- IMAMOTER (Consiglio Nazionale delle Ricerche) – Tribology
- ITT – Manufacture of brake pads

Phosphor thermometry (intensity ratio)

- NPL National Physical Laboratory – Phosphor thermometry development, traceable calibration techniques
- University of Strathclyde – Development of phosphor thermometer for online/offline monitoring; AFRC provide access to industrial processes
- Danish Technological Institute – Development of phosphor thermometer
- BAE Systems – Provide access to marine manufacturing for trials

Thermocouple thermometry

Czech Metrology Institute, Univerza v Ljubljani, TÜBİTAK, NPL National Physical Laboratory, PTB, CEM Centro Español de Metrología, Danish Technological Institute – Traceable calibration facilities

Johnson Matthey, CCPI Europe Limited, University of Cambridge – Supply of thermocouple wire

Combustion thermometry

- NPL National Physical Laboratory – Supply, calibrate portable standard flame
- DTU – Develop IR, UV spectroscopy
- B&W vølund – Provide access to waste incineration facilities for trials
- SENSIA – Development of IR imaging devices
- Universidad Carlos III de Madrid – Development of optics and IR instrumentation

Fibre-optic thermometry (hybrid BB/FBG)

- Leibniz IPHT – Development of laser and fibre-optic technologies
- Justervesenet – Development of sapphire based sensors; traceable calibration techniques
- PTB – Development of FBG fibre-optic sensors
- MUT Advanced Heating – Provide access to industrial furnace manufacturing for trials
- Elkem – Provide access to silicon processing for trials

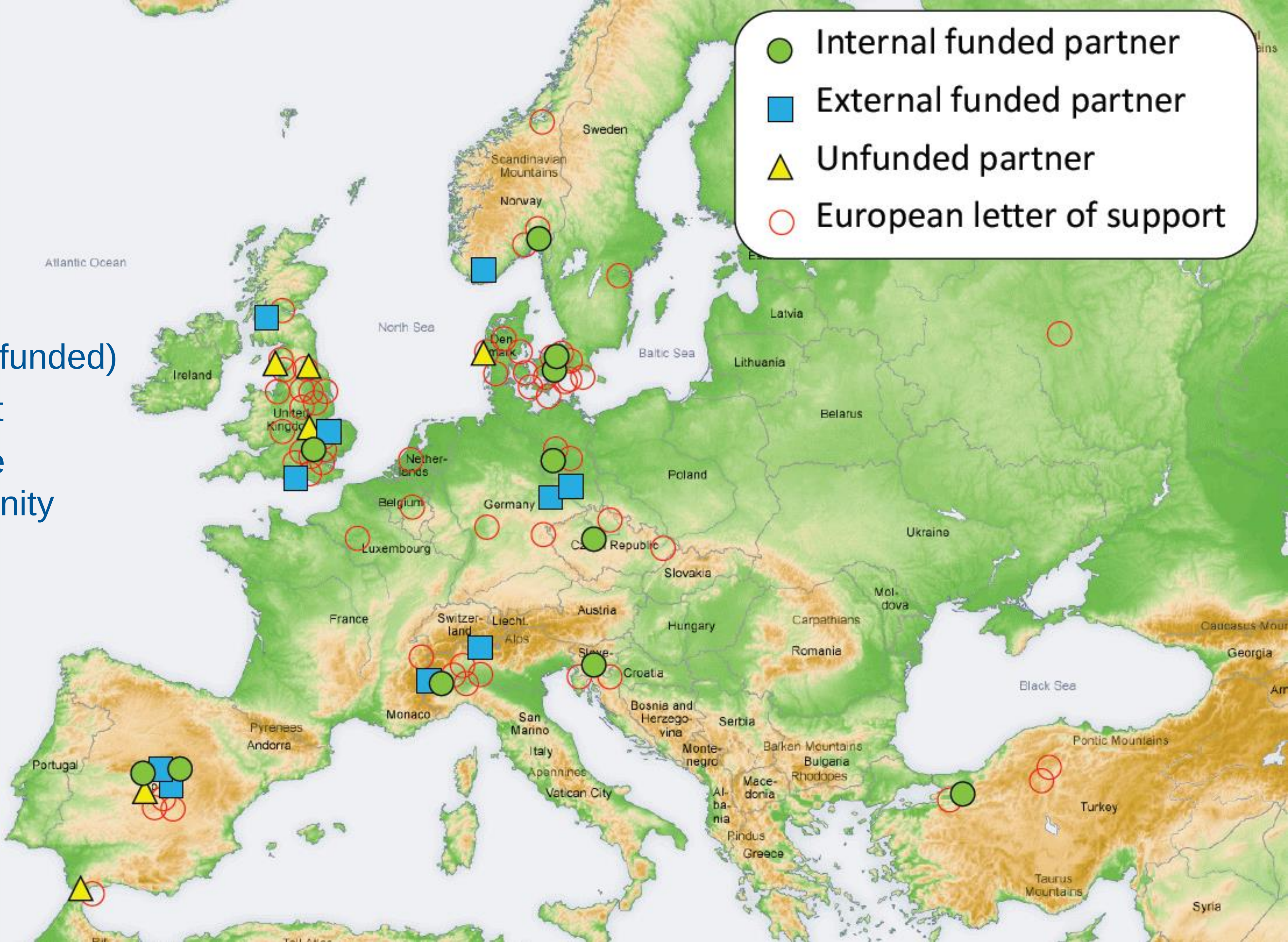
Fibre-optic thermometry (hollow-core/bundles)

- University of Southampton – Optical fibre development, instrumentation
- NPL National Physical Laboratory – Development of traceable calibration techniques

Fibre-optic thermometry (distributed)

- CSIC – Development, manufacture and testing of DTS fibre-optic thermometers
- Acerinox – Manufacture of stainless steel
- CEM Centro Español de Metrología – Development of traceable calibration techniques

- 11 NMIs
- 4 universities
- 11 companies (6 unfunded)
- 67 letters of support
- 142 members of the stakeholder community



- EMPRESS 2
  - Phosphor thermometry
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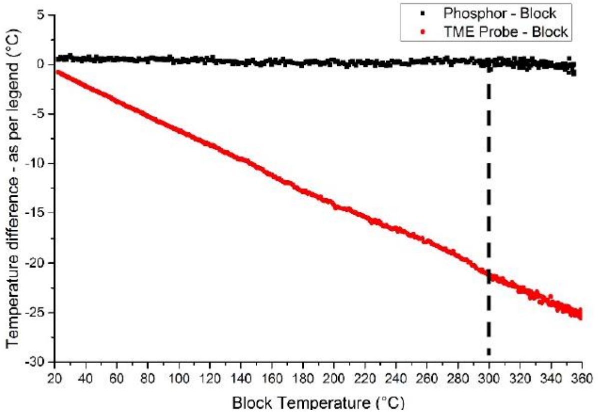
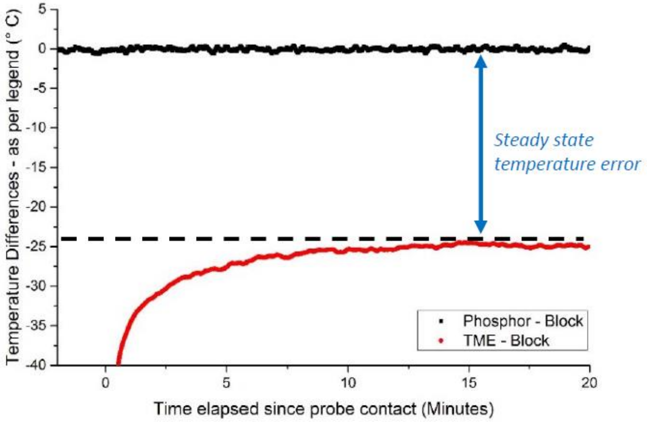
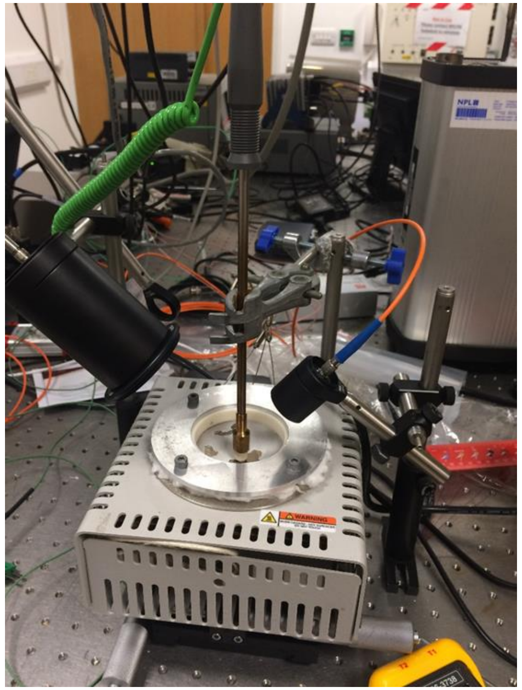
- Practical Johnson noise thermometry

“Impossible” reliable surface temperatures

- Contact sensors, slow, extract heat from surface, time consuming, also have large unquantified errors >> 10 °C
- Radiance based methods, emissivity, reflected radiation can lead to large unquantified errors >> 10 °C

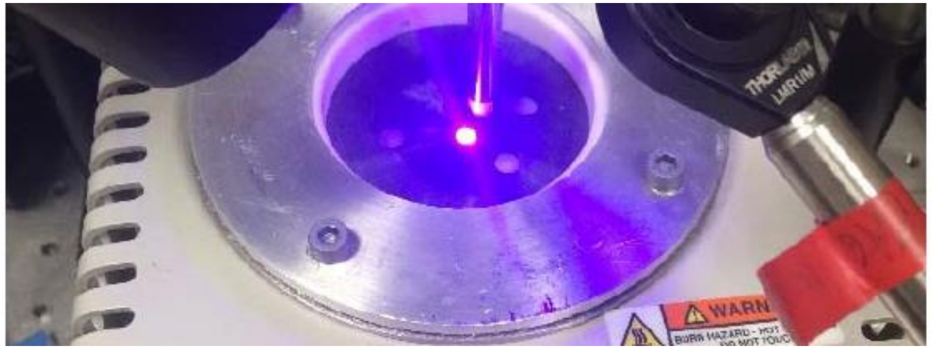


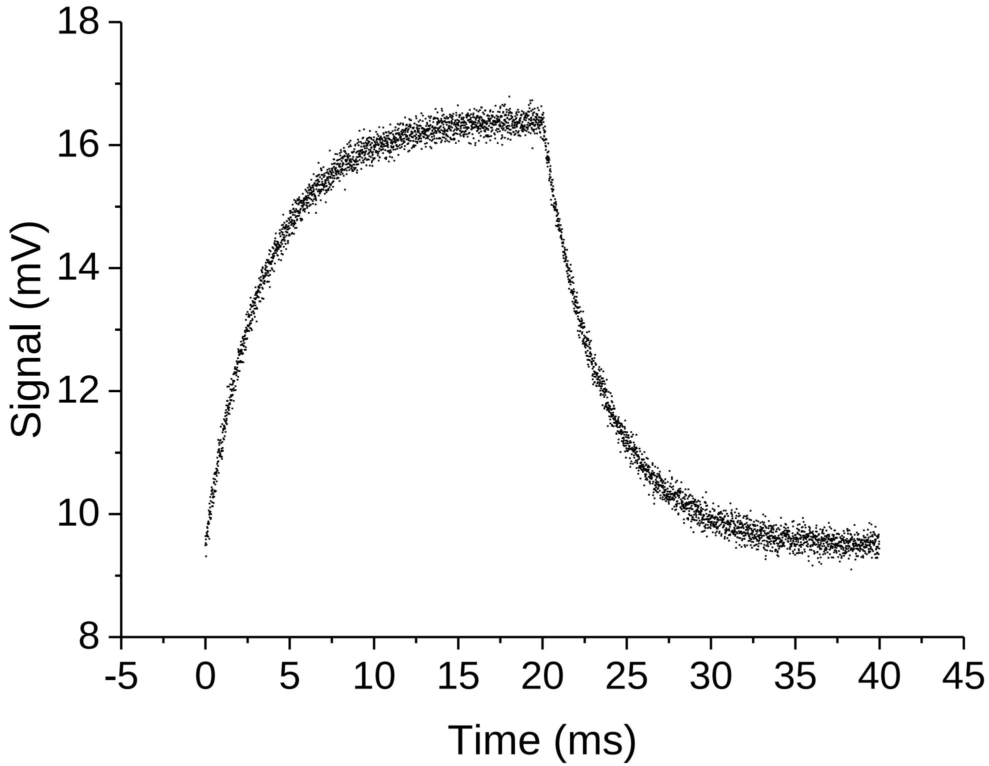


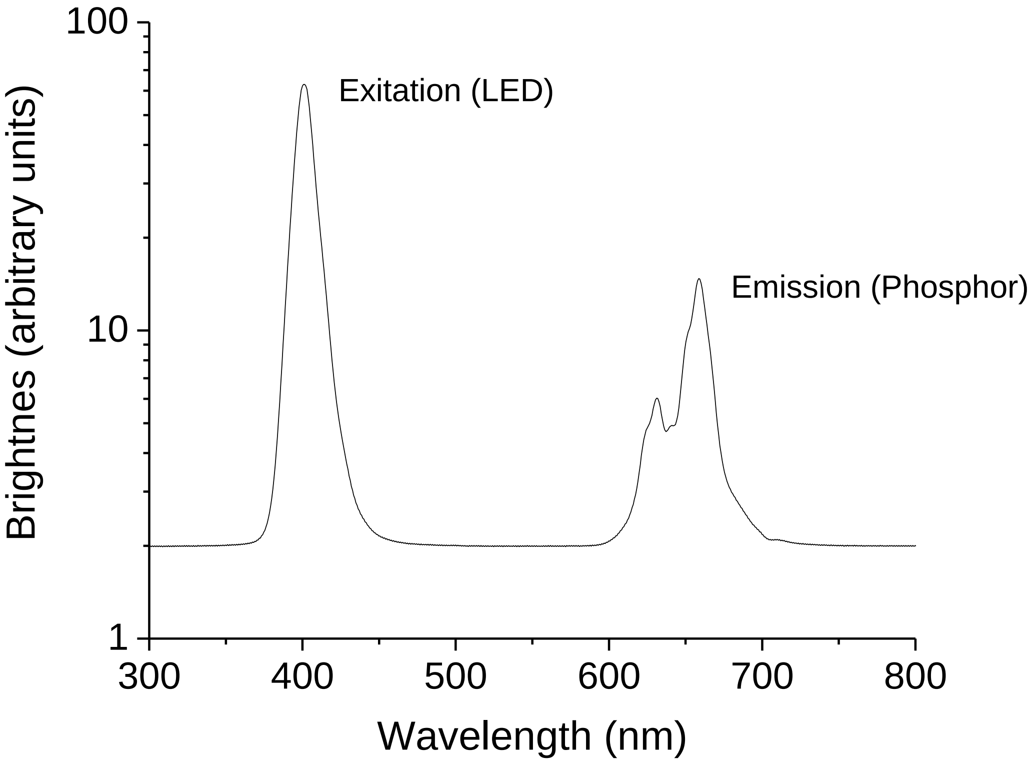


Non-contact non-radiance traceable surface thermometry

- Apply specific phosphor to surface and activate
- Either – decay time of emitted light
- Or – 2 line ratio method





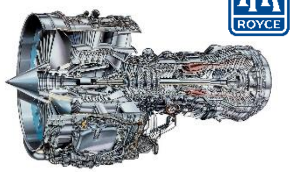


WP1 Phosphor thermometry

Loughborough University

Rolls Royce

NPL National Physical Laboratory



INPUT FROM WP4

NPL
Develop traceable 2D intensity ratio phosphor thermometer

NPL
Combine with thermal imaging

STRAT, NPL, DTI
Develop phosphor thermometry for temperature mapping of forging tool

INRIM, ITT, CNR
Develop phosphor thermometer to 1000 °C in conjunction with on-site fibre optic probing and sensing

NPL, INRIM
Validate at NPL, or locally, using either
- ITS-90 fixed points
- Comparison calibration
- Phosphor thermometer-based surface calibrator

NPL, STRAT
Determine emissivity of test samples with spot pyrometer, compare with phosphor thermometer

NPL, STRAT
Testing of phosphor applied to billets during heat treatment

NPL, BAE
Testing of phosphor applied to welding applications

NPL, DTI, AGH
Test in glass manufacturing process

STRAT
Test STRAT phosphor thermometer (online and offline devices) in AFRC forging environment

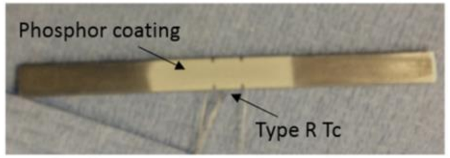
INRIM, ITT, CNR
Test in brake pad characterisation application; metallurgical analysis

DTI
Revise EURAMET best practice guide on surface temperature measurement (developed in EMPRESS) to include phosphor thermometry techniques

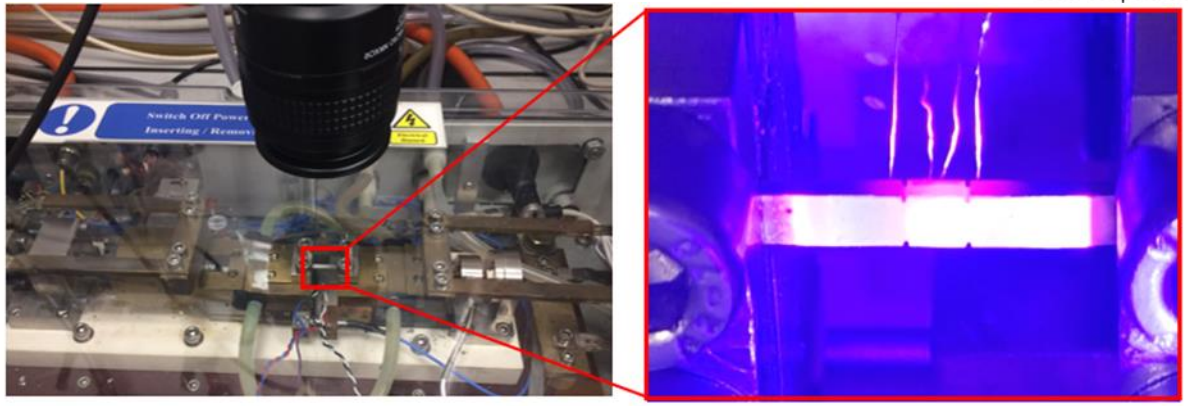
Sensors available for exploitation
- 2D intensity ratio phosphor thermometer to 1000 °C
- Combined intensity ratio phosphor thermometer/thermography system to 1000 °C

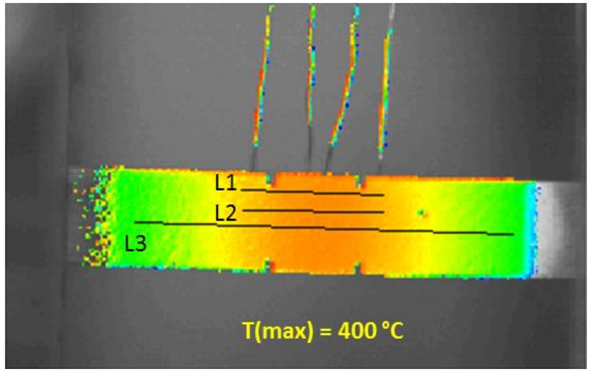
Phosphor thermometry

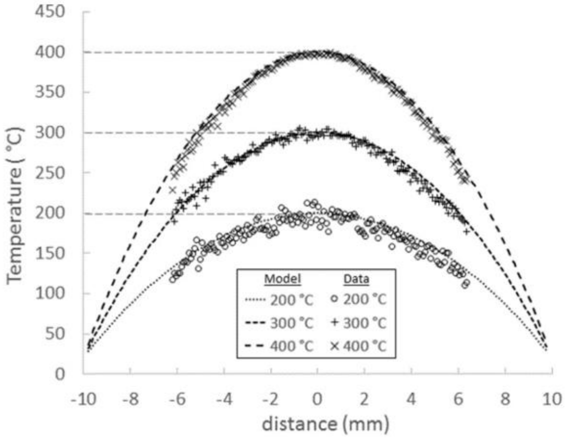
NPL National Physical Laboratory



Steel coupon: 3 mm x 1 mm x 20 mm

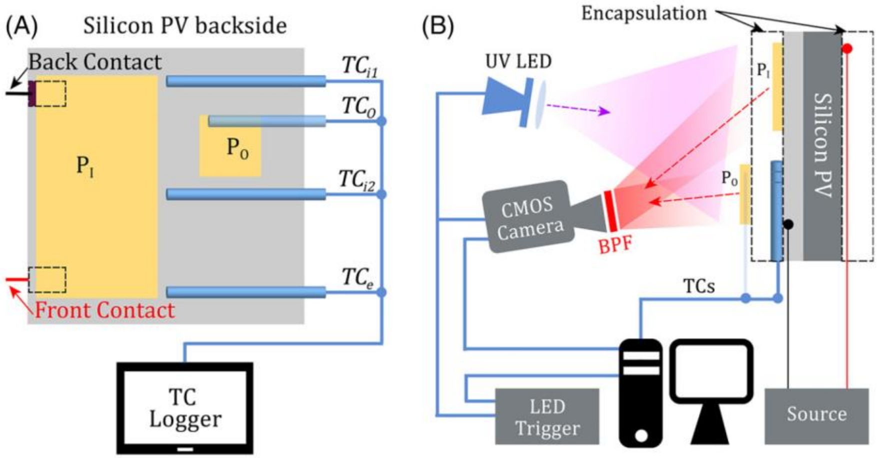


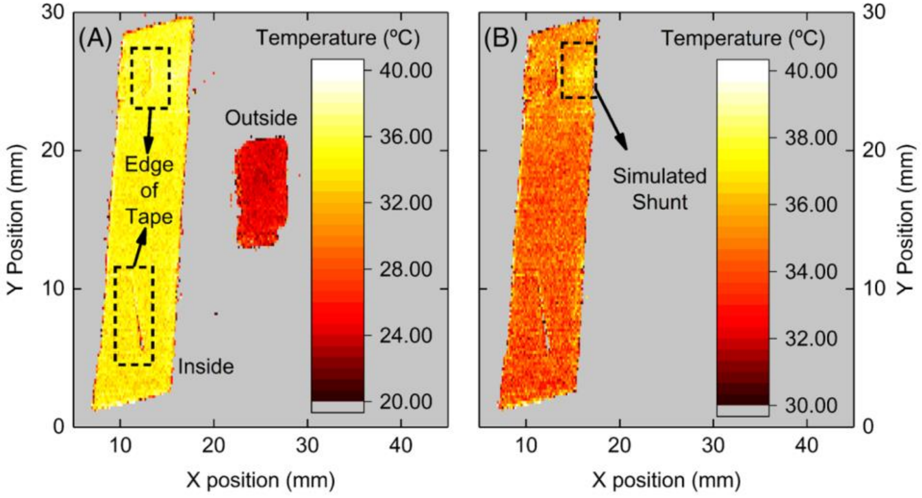




Sutton et al. Meas. Sci. Technol. 30 (2019) 044002

- Meet standards for pre- and post-welding heat treatment
- BS EN 13445, ASME VIII, PD5500, ISO 15614-1
- ISO 8502-4:2000 for coating





Cao, Koutsourakis, Sutton, et al.
Prog Photovolt Res Appl. 2019; 27 673–681

- EMPRESS 2
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WP2 Standardising high stability thermocouples

NPL National Physical Laboratory

Standardisation of Pt-40%Rh/Pt-6%Rh thermocouple

PTB, CCPI, NPL, CEM, CMI, DTI, TUBITAK, UL, JM
Construct thermocouples according to agreed procedure, and perform calibration with all available facilities

UL, PTB, NPL, CEM, CMI, DTI and TUBITAK
Provide draft reference function to IEC committee

NPL, DTI (& collaborator e.g. Ardagh Glass Holmegaard)
Trial in e.g. glass manufacturing to 1700 °C as a demonstration of achieved stability, and of the reference function

PTB, MUT
Trial the Pt-Rh thermocouples in industrial furnace manufacturing

UL (& collaborator e.g. Kambic)
Trial the Pt-Rh thermocouples in industrial furnace manufacturing

CMI (& collaborator e.g. Trinecke Zelezarny)
Trial the Pt-Rh thermocouples in steel manufacturing facility

Optimisation of double-walled MI thermocouple stability up to 1250 ° C

CCPI, UCAM
Manufacture and supply double-walled and single-walled MI thermocouples

UCAM, CCPI
Optimise inner to outer wall thickness ratio with respect to drift rate

UCAM, CCPI
Metallurgical analysis of selected DW MI cables

PTB, CEM, CMI, NPL,TUBITAK, UL
Assess stability of double-walled MI cable of selected types (K,N) and cable diameters and compare with conventional cable

UL
Assess influence of electrical and magnetic fields on operation of the DW MI cables

NPL, UCAM, CEM, CCPI
Develop technique for quantifying insulation resistance of MI thermocouples as a function of temperature

NPL, CEM, UCAM, CCPI
Develop mitigation for insulation resistance breakdown of MI thermocouples

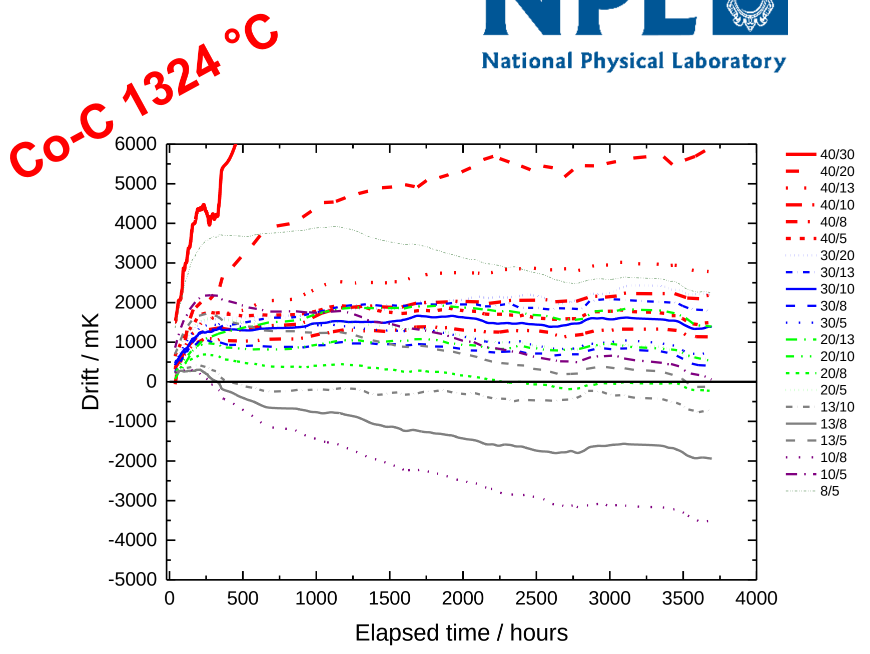
NPL, PTB, CCPI, CEM, CMI, TUBITAK, UCAM, UL

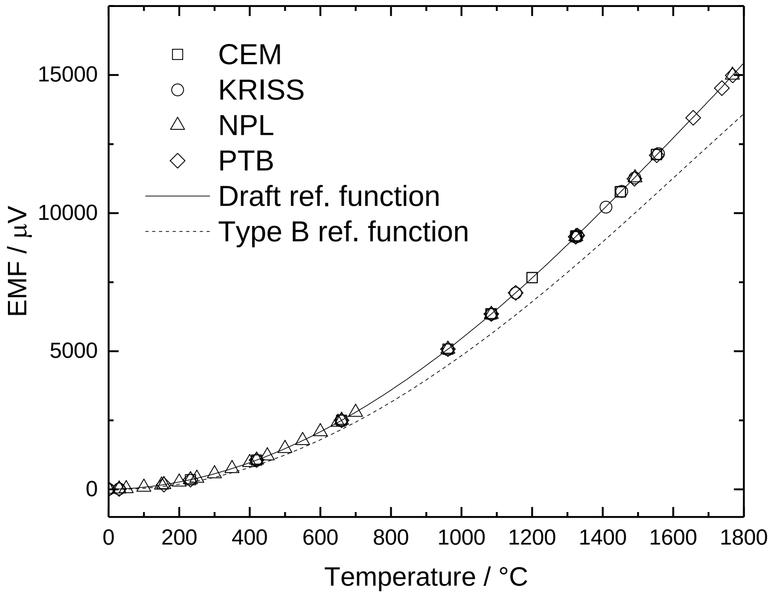
Prepare joint peer-reviewed publication on the performance of DW MI thermocouples.

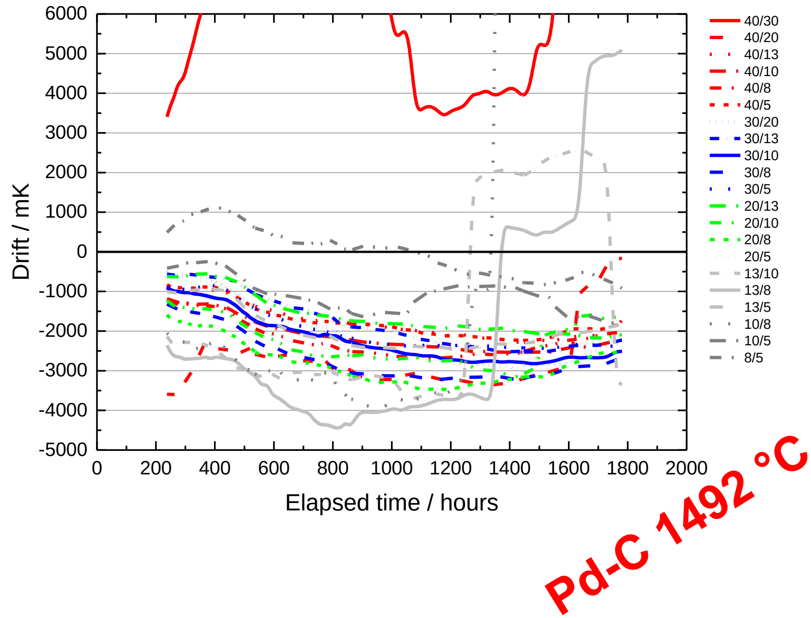
Provide evidence to IEC61515 committee that stability, insulation resistance, and time response of DW MI thermocouples are comparable to, or better than, conventional MI thermocouples

Pt-Rh thermocouples

- Systematic evaluation of stability of a large number of different Pt-Rh thermocouples using multi-wire thermocouple and ***HTFPs*** (NPL, PTB)
- Optimum Pt-40%Rh/Pt-6%Rh
- Preliminary reference function (NPL, PTB, CEM, KRISS)
- IEC TC 65/SC 65B/WG5
- EMPRESS 2: 7 European NMI participants





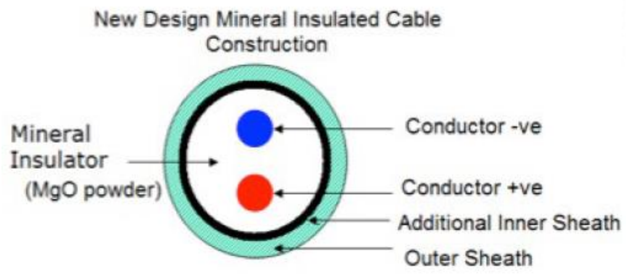


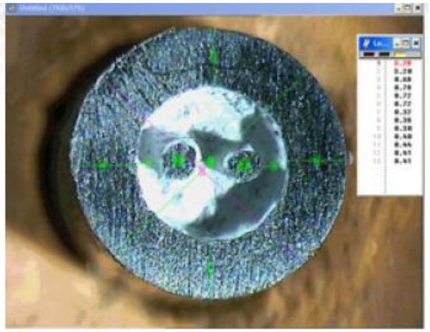
Double-walled MI thermocouples

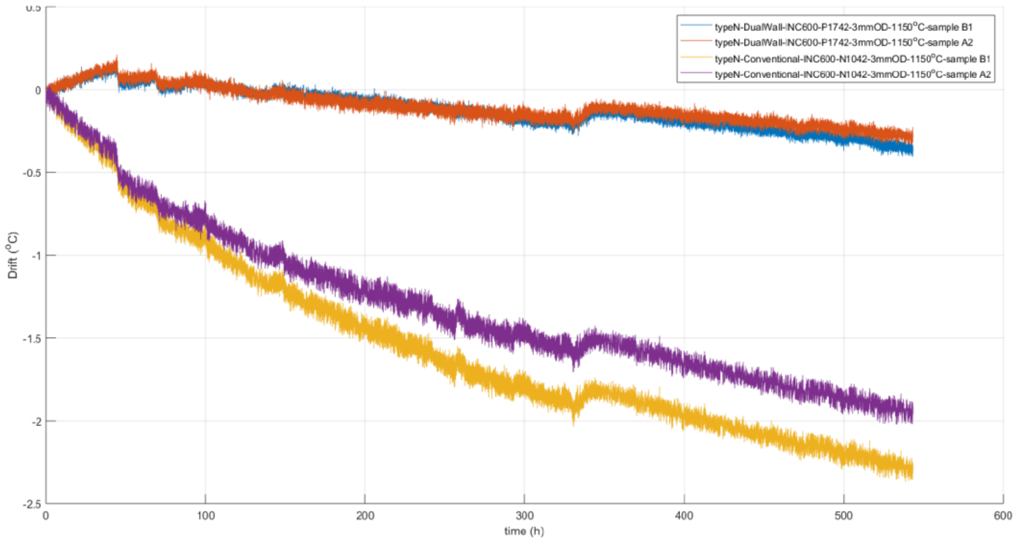
- Stability
- Optimal ratio of wall thicknesses
- Insulation resistance breakdown
- Lay framework for standards e.g. relax dimensional requirements of IEC 61515:2016, AMS2750E
- Presented to SAE (Nadcap), IEC TC 65/SC/65B/WG5

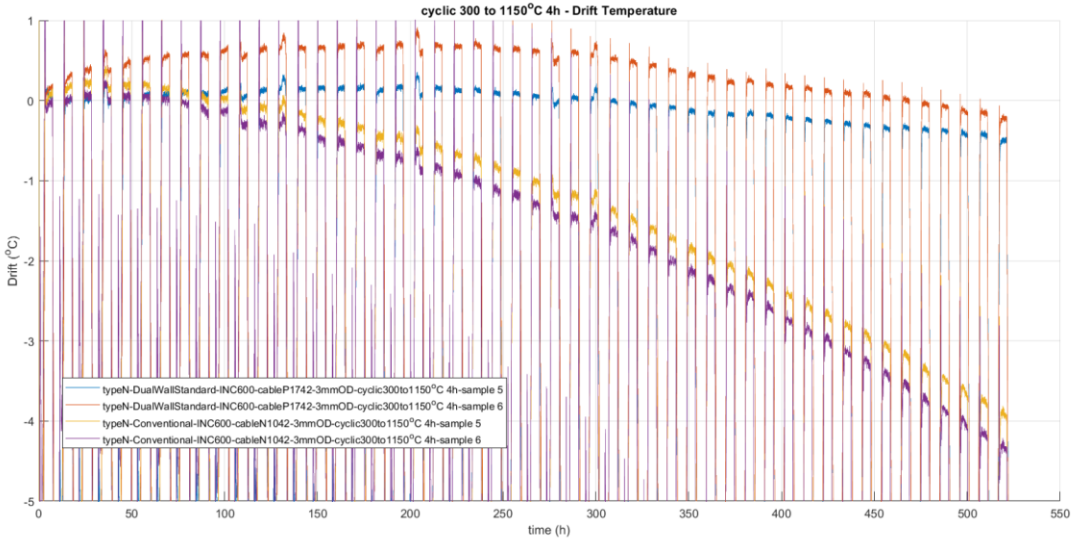
UNIVERSITY OF CAMBRIDGE

CCPI Europe Limited







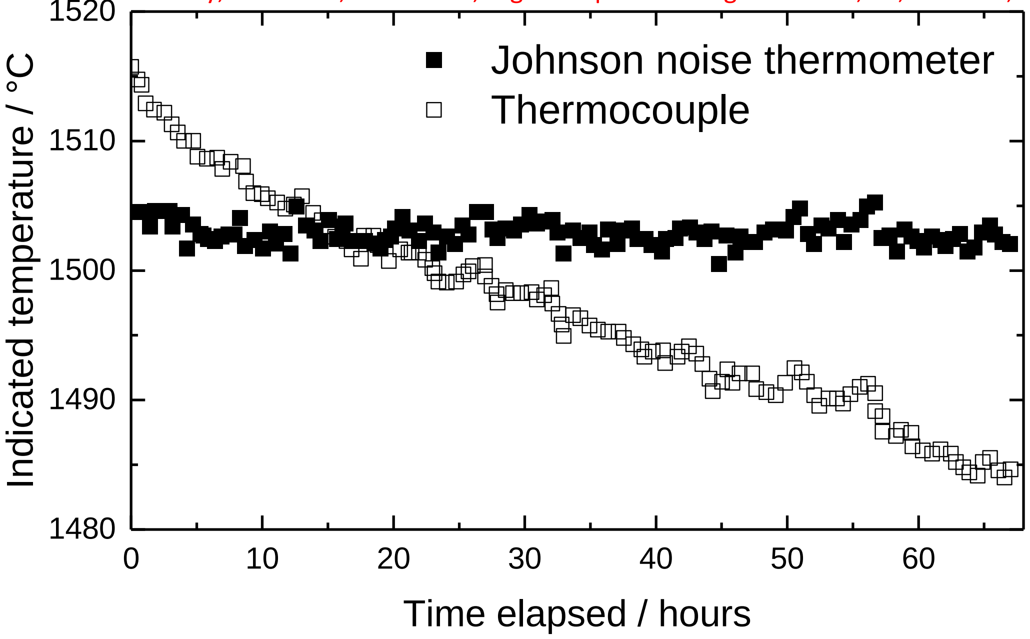


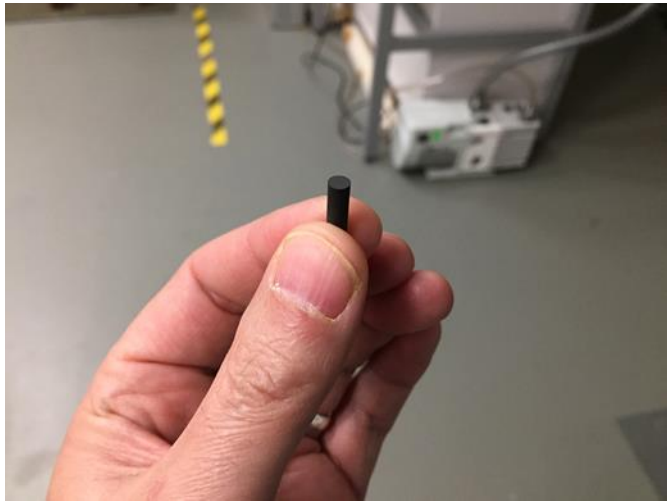
Self-validating thermocouples

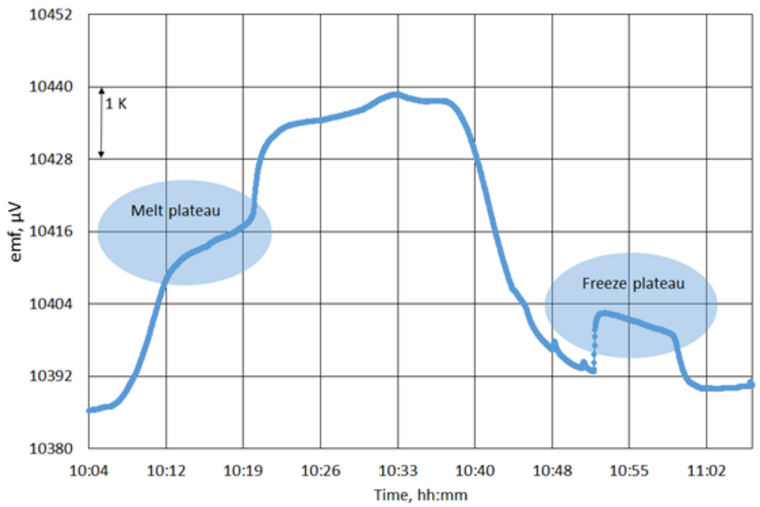
National Physical Laboratory

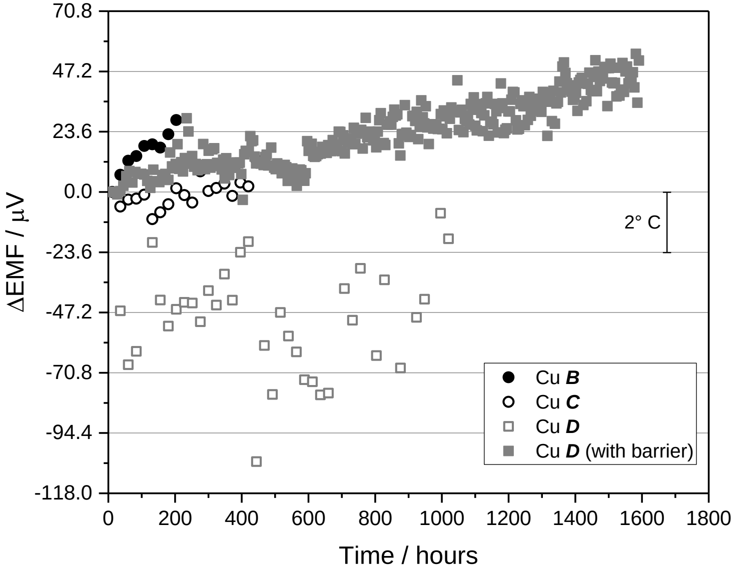
- Even noble metal thermocouples can drift by as much as tens of degrees
- No visible sign in-process of this happening
- Self-validation for in-process calibration/traceability
- Develop miniature fixed points
- Same format as conventional sensors
- Robust

H. Brixy, R. Hecker, J. Oehmen, High Temperature High Pressure, **23**, 625-631, 1991



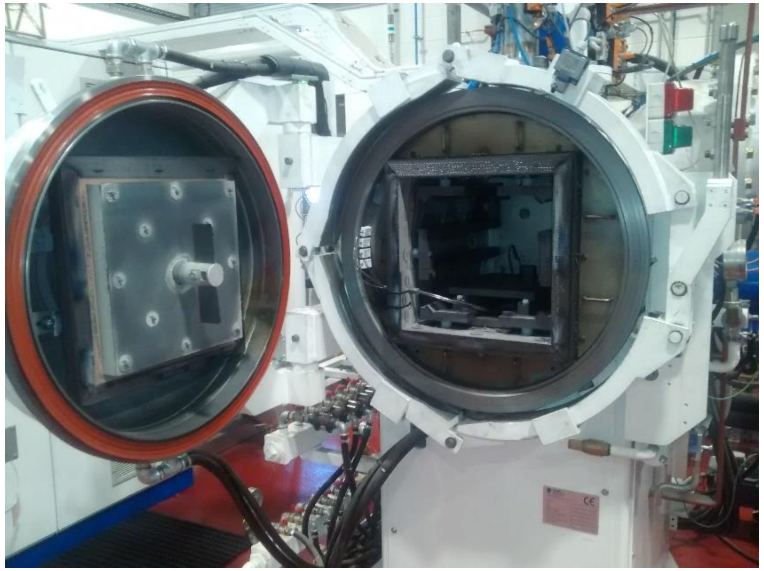






In-situ thermocouple trials

NPL
National Physical Laboratory



Bodycote

AFRC
ADVANCED FORMING RESEARCH CENTRE
UNIVERSITY OF STRATHCLYDE

ICPE-CA

- EMPRESS 2
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  - Combustion/flame thermometry
  - Fibre-optic thermometry
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WP3 Combustion thermometry

NPL
Supply and coordinate circulation (and calibration) of portable standard flame

Develop low-cost thermal imaging system

UC3M, DTU
Use high res measured emission spectra to simulate low res spectra; explore relation between spectral resolution and T accuracy; design filters for optimal centre wavelengths and spectral bandwidths

CEM
Calibrate IR cameras to provide traceability of UC3M measurements

UC3M, SENSIA, CEM 3.2
Develop multispectral imaging device and calibrate

UC3M, NPL
Calibrate against NPL standard flame and other flame sources

UC3M, SENSIA
Trials on various flame sources

Sensors available for exploitation
- Low resolution, economical multispectral imaging flame thermometer
- FTIR sweeping emission flame thermometer system

FTIR on-sight/sweeping

DTU, UC3M
Selection of optimal T retrieval algorithm from previous task

DTU
Develop FTIR on-sight/sweeping emission measurement system or 2D profiles using portable standard flame as a reference

DTU, NPL
Testing and calibration of developed FTIR against NPL standard flame; target uncertainty 0.5%

DTU, B&W Volund
Perform in-situ 2D temperature profile measurements for optimisation of NO_x SNCR processes, and validation of CFD modelling of a waste incinerator

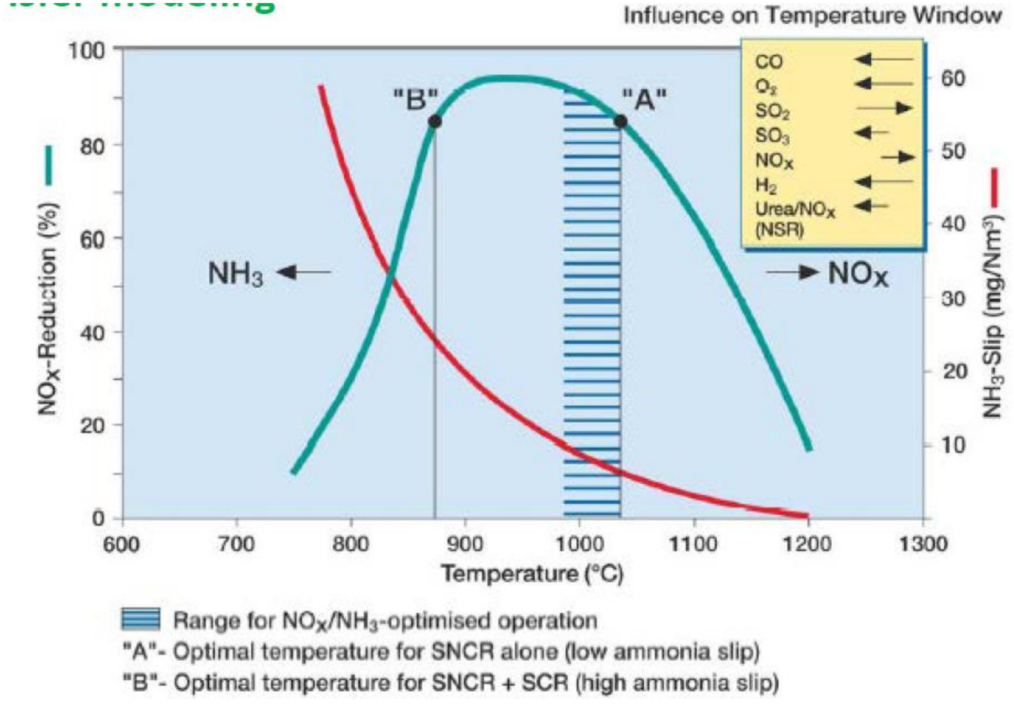
DTU, CEM, NPL, SENSIA, UC3M, VOLUND
Write papers and trade journal articles to outline findings and demonstrate linkage between portable standard flame & improved process efficiency


DFWM/LIGS
Nd:YAG laser
355 nm
532 nm
Dye laser
~624 nm
SFG
~226 nm
BP
Trace
Probe
DFWM Probe
DFWM Trace
PMT
LITGS signal
DFWM signal
Iceland
Norwegian Sea
Sweden
Scandinavian Mountains
Norway
Ural Mountains
Russia
Ireland
Belarus
Poland
Ukraine
Czech Republic
Slovakia
Austria
France
Portugal
Spain
Pyrenees
Andorra
Caucasus Mountains
Georgia
Armenia
Syria
Fully validated portable standard flame
Hyper-spectral imaging
CENTRO ESPAÑOL DE METROLOGÍA
CO2 (ppm.m) - NPL Std Flame - φ = 1 No co-flow
Q CO2 = 3452

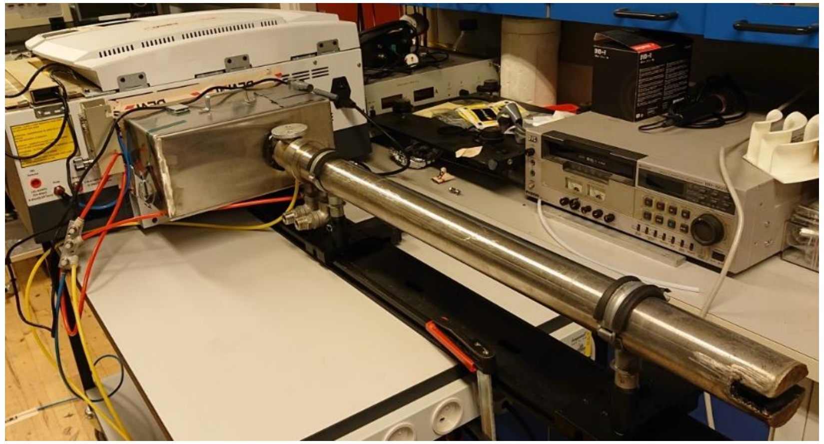
NOx SNCR

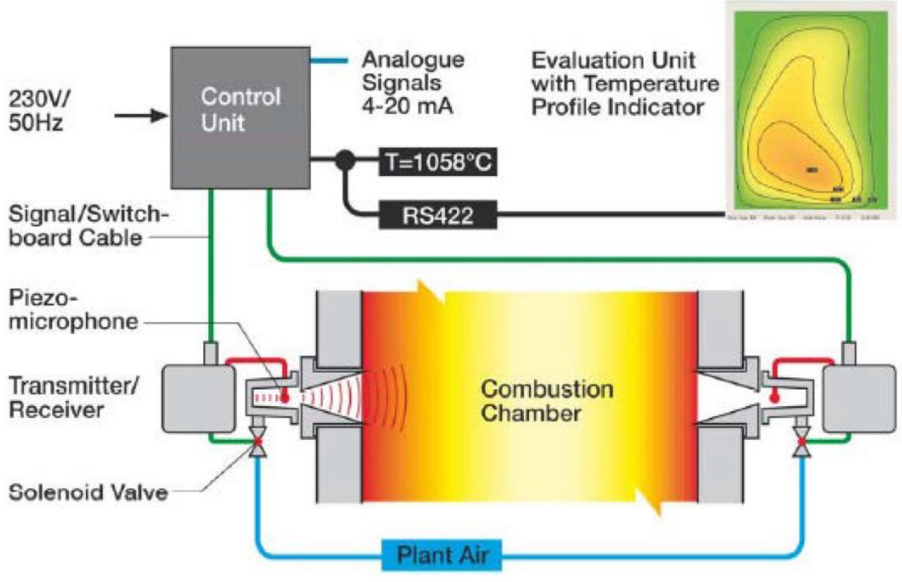
- NOx SNCR process: NH3/urea injection optimisation
- Very narrow band of temperatures for optimal NOx reduction
- NOx, CFD and radiative heat transfer modelling

- Goals:
- Process optimisation through *in-situ* temperature control
- Improved boiler design, more efficient process



Images: Alex Fateev, DTU





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WP4 Harsh environments: fibre-optics

Phosphor-based fibre optics

NPL, DTI
Select and traceably calibrate phosphor to 1000 °C

ALSO AS INPUT TO WP1

NPL, DTI
Develop phosphor-based fibre-optic thermometer to 660 °C

Hollow-core fibre thermometer

SOTON, NPL
Develop hollow core fibre phosphor tipped thermometer (including instrumentation) immune to gamma radiation

SOTON, NPL
Develop mid-IR ther
imaging fibre bundle
remote inspection o
reach/hostile enviro
using fibre bundles

Brillouin scattering DTS thermometer

CSIC, CEM, FOCUS
Design and optically characterise the Brillouin Scattering distributed sensor

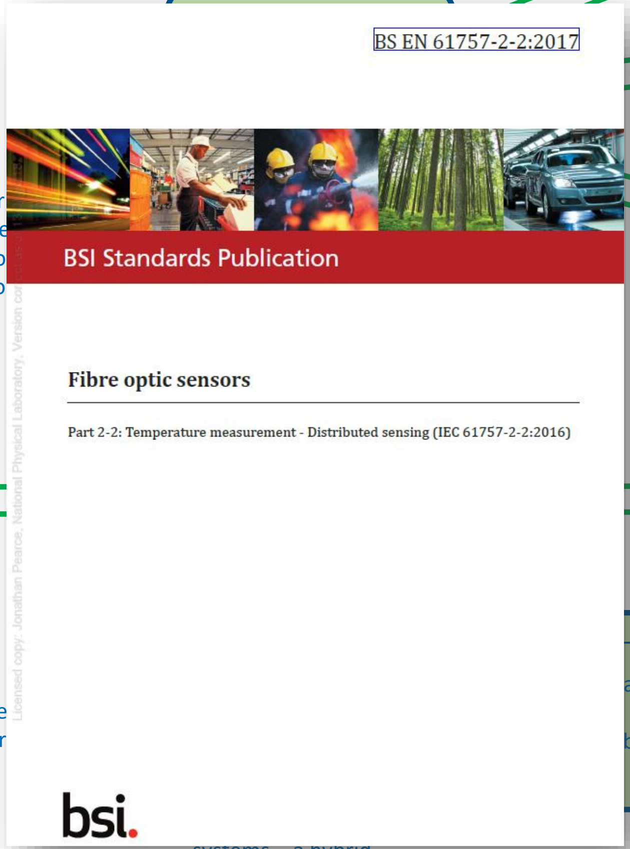
Fibre-optic and BB-based thermometer

JV, PTB, IPHT
Develop instrumentation on system-wide level (optoelectronics, signal processing) for traceable FBG thermometer based on sapphire fibre to 1500 °C

JV, PTB, IPHT
Develop metallic or ce
cavity to create BB for
tip

HT
ate in
bility

systems – a hybrid

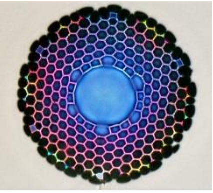

BS EN 61757-2-2:2017

BSI Standards Publication

Fibre optic sensors

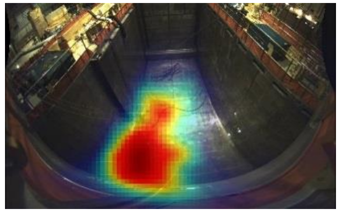
Part 2-2: Temperature measurement - Distributed sensing (IEC 61757-2-2:2016)

bsi.



Trial in plasma storm of charged particles and large magnetic fields at collaborator e.g. Danfysik

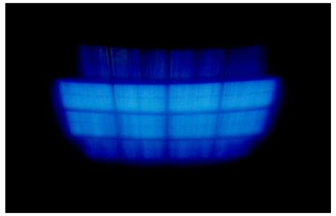
SOTON, NPL
Trial in gamma ray environment at NPL or e.g. Sellafield



SOTON, STRAT
Trial in forging/forming process at AFRC

CEM, CSIC, ACERINOX
Perform in-situ trials of the TDS in the facilities of ACERINOX – stainless steel manufacturing

JV, PTB, NPL, IPHT, MUT, ELKEM
Trial in-process at ELKEM, MUT, and NPL's gamma-ray facility



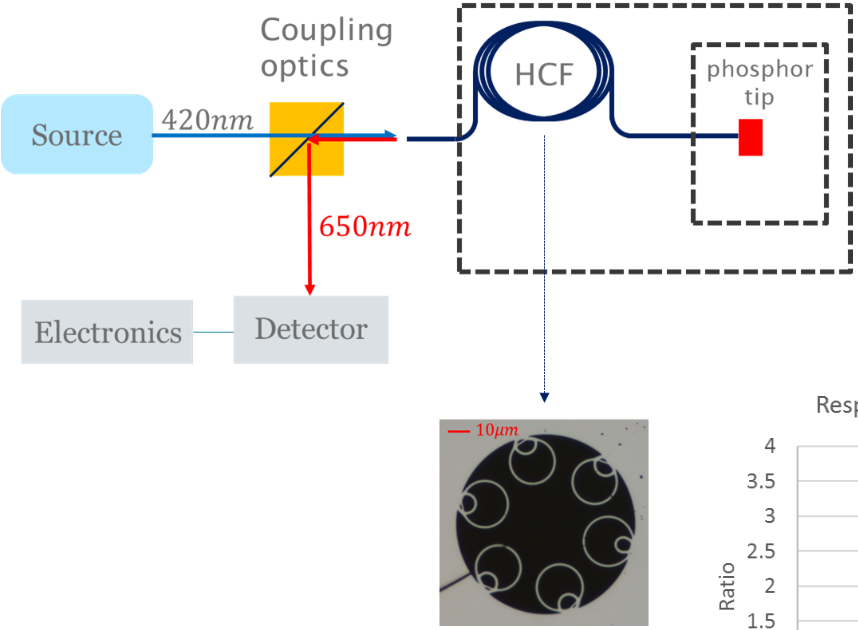
Sensors available for exploitation

- Two phosphor-based fibre-optic thermometers with separately developed instrumentation, cross-validated, to 650 °C
- Hollow-core phosphor-tipped fibre-optic thermometer suited to harsh environments e.g. ionising radiation, magnetic fields to 1000 °C
- Thermal imaging fibre bundle system for remote inspection to 1000 °C
- Distributed fibre-optic temperature sensor based on Brillouin scattering to 650 °C
- Hybrid blackbody/FBG fibre-optic thermometer to 1500 °C

Fibre-optic phosphor thermometer

NPL National Physical Laboratory

- Regular & hollow-core phosphor tipped
- Traceable calibration
- Hollow core fibre exposed to gamma radiation



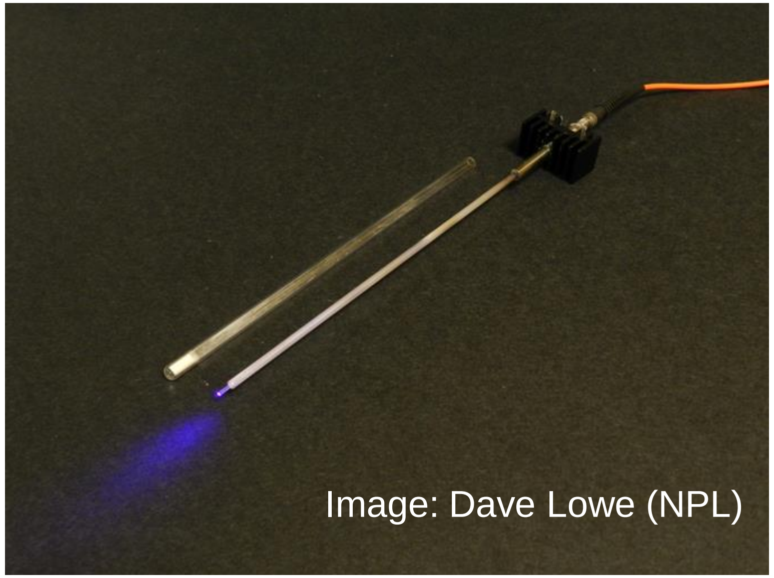
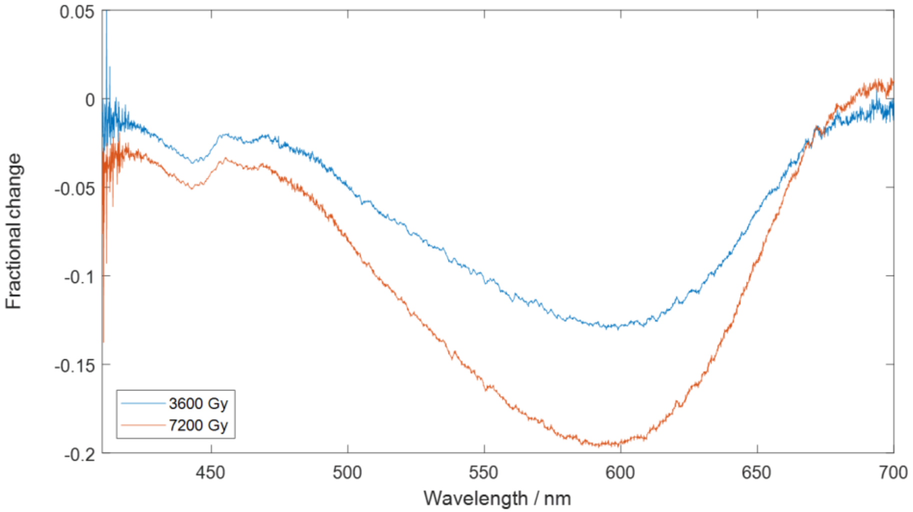
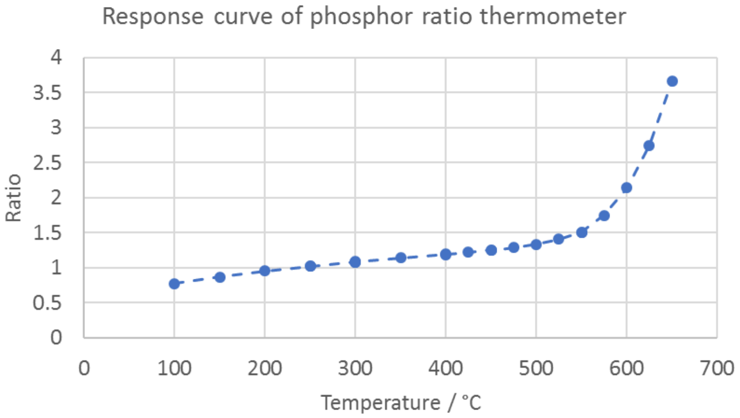
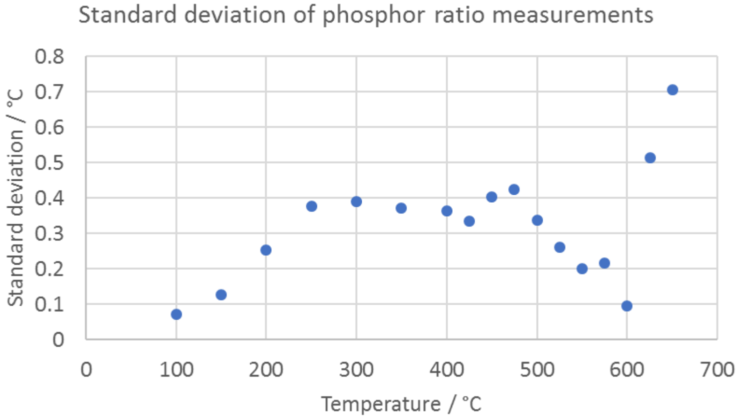


Image: Dave Lowe (NPL)



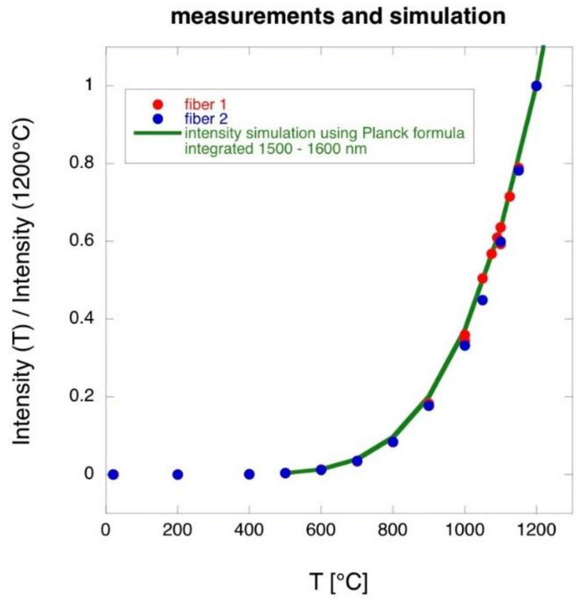


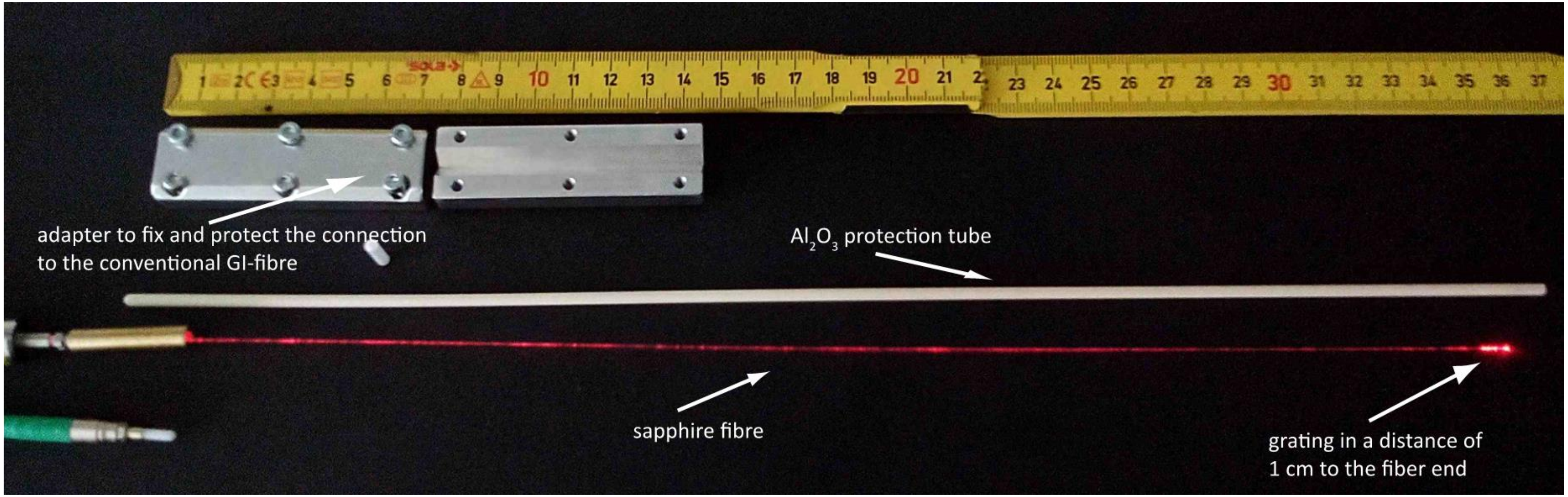


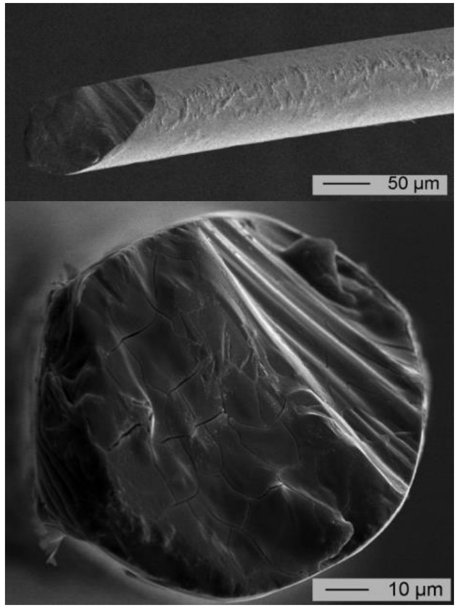
Hybrid fibre-optic based sensor to 1500 °C

- Sapphire fibre Bragg grating
- Temperature dependence of spectral reflectivity
- Project objective: Characterisation and ITS-90 traceable calibration up to 1500 °C
- Long-term objective: very precise T measurement between 1600 °C and 1900 °C
- Stephan Krenek (PTB)

Justervesenet







VSL Dutch Metrology Institute
NMi
METROSOL Metrology Solutions
SIEMENS
JM Johnson Matthey Inspiring science, enhancing life
NASA
activespace technologies making space a global endeavour
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AFRC ADVANCED FORMING RESEARCH CENTRE UNIVERSITY OF STRATHCLYDE
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Heraeus Electro-Nite
LNE Le progrès, une passion à partager
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HALDOR TOPSØE
E4U
Farsund Aluminium Casting AS
TECHNISCHE UNIVERSITÄT DARMSTADT
IEC
SAFRAN AIRCRAFT ENGINES
nmisa National Metrology Institute of South Africa
bp
Elkem
SEABORG
AUBERT&DUVAL
HTM
R. D. WEBB COMPANY INC established 1986
OXSENSIS
MSL Measurement Standards Laboratory of New Zealand
TATA
Resonate TESTING LIMITED
CeresPower
UNIVERSITY OF BIRMINGHAM
PTB Physikalisch-Technische Bundesanstalt Braunschweig und Berlin
BAE SYSTEMS
mtc Manufacturing Technology Centre
YARA
KELVIN TRAINING
ROLLS ROYCE
B&W vølund
The University Of Sheffield.
Campden BRI food and drink innovation
IOP Institute of Physics Instrument Science and Technology Group
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TRM & MICC Ltd www.temperature-house.com
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KRISS 한국표준과학연구원 Korea Research Institute of Standards and Science
GMG s.r.l.
ISOTECH The Source for Calibration Professionals
Esterline
le cnam
The Welding Institute
Exova METECH
NIM 中国计量科学研究院 National Institute of Metrology (NIM), China
RAL Space
HT MT High Temperature Mechanical Testing Committee
MUT ADVANCED HEATING
University of Brighton
INM Instituto Nacional de Metrología de Colombia
pemit
DONGDA SENSOR
gamma forgiati
sbs SCANDINAVIAN BRAKE SYSTEMS
WARWICK THE UNIVERSITY OF WARWICK
TESEY MANUFACTURING COMPANY, Ltd
TU/e Technische Universiteit Eindhoven University of Technology
enagas
LAND AMETEK PROCESS & ANALYTICAL INSTRUMENTS
Loughborough University
LBT TESTING & CALIBRATION
OTTO VON GUERICKE UNIVERSITÄT MAGDEBURG
EVOLUTION MEASUREMENT
University of Huddersfield
H&B SENSORS
OMEGA
Elimko
NETZSCH
ВНИИМ 1842
ICPECA
University of Strathclyde Glasgow
SENSOR THERM
TIMET
INSTRON
CETIAT ensemble, innover et valider
itma MATERIALS TECHNOLOGY
ELITE
GEC Instruments Precision Temperature and Humidity Instrumentation
LUMENISITY
HYDRO
LASERLAM
EURAMET
Hidria
ACCREDIA L'ENTE ITALIANO DI ACCREDITAMENTO
DANFYSIK
Inst MC Institute of Measurement and Control
ALSTOM
CARBOLITE GERO 30-3000°C
Kambic metrology
OSRAM
TSE
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VP industries
SENSIA
sapa:
Brunel University London
SHAWCOR
EDF ENERGY
Sellafield Ltd
ACERINOX
ellab Validation Solutions
Svendborg Brakes
ArdaghGroup
UNIVERSITY OF CAMBRIDGE
INL Idaho National Laboratory

Workshop (x2)

- ~60 delegates
- ~40 organisations

Wednesday 18 April 2017

9.00	Arrival and registration		Introduction & keynote
9.30	Welcome and introduction	Graham Machin, NPL	
9.40	Overview of the EMPRESS project	Jonathan Pearce, NPL	
10.00	The re-definition of the kelvin	Michael de Podesta, NPL	
10.30	Update on the development of a practical Johnson noise thermometer	Paul Bramley, Metrosol	
11.00	Coffee break		
11.30	Overview of WP1: Low-drift contact temperature sensors to above 2000 °C	Frank Edler, PTB	Contact thermometry
11.50	Overview of WP2: Zero-drift contact temperature sensors to 1350 °C	Claire Elliott, NPL	
12.10	Graeme Young: Sensing challenges in the oil & gas industry	Graeme Young, Marmon Engineered Wire & Cable	

EMPRESS Workshop

A one-day conference on enhanced temperature measurement techniques for improved process control held on 22 March 2017

Advanced Forming Research Centre,

www.npl.co.uk/events

	Wedn		
9.00	Arrival and registration		
9.30	Welcome to the AFRC		
9.35	Welcome and introduction		
9.40	Overview of the EMPRESS pr		
10.00	Keynote: Temperature meas processes to create better pr		
10.40	Overview of WP1: Low-drift sensors to above 2000 °C		
10.50	Overview of WP2: Zero-drift sensors to 1350 °C		
11.00			
11.30	Introduction to a new low dr thermocouple mineral insulated cable technology	University & Trevor Ford, CCPI Europe Ltd	Contact thermometry
11.50	Optical based contact thermometer using SiC, quartz tubes and sapphire fibre	Sigurd Simonsen, Elkem	
12.10	High-temperature measurement in industrial practice	Jurgen Blüm, MUT	
12.30	Lunch		
13.30	Overview of WP3: Traceable surface temperature measurement with contact sensors	Lucia Rosso, INRiM	Phosphor thermometry
13.40	Thermocouples in industrial environments	Mark Thomas, BAE Systems	
14.00	Surface thermometry in low TRL testing of combustor cooling concepts	Clare Bonham, Loughborough University	
14.20	Industrial uses of thermographic phosphors	Andy Heyes, Strathclyde University	
14.40	Tea break and networking		
15.10	Overview of WP4: Traceable combustion temperature measurement	Gavin Sutton, NPL	Combustion thermometry
15.20	Laser techniques for flame and combustion thermometry	Paul Ewart, Oxford University	
15.40	Temperature measurements in turbulent flames using Raman spectroscopy	Wolfgang Meier, DLR	
16.00	A practical Johnson noise thermometer	David Cruickshank, Metrosol	
16.45	Tour of AFRC		

NPL National Physical Laboratory

AFRC Advanced Forming Research Centre, University of Strathclyde

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Institute of Measurement and Control

IOP Institute of Physics Instrument Science and Technology Group

Jonathan Pearce
Joined group: Jan 2017

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The Thermocouples in Industry group, has been formed to provide an open-access place for

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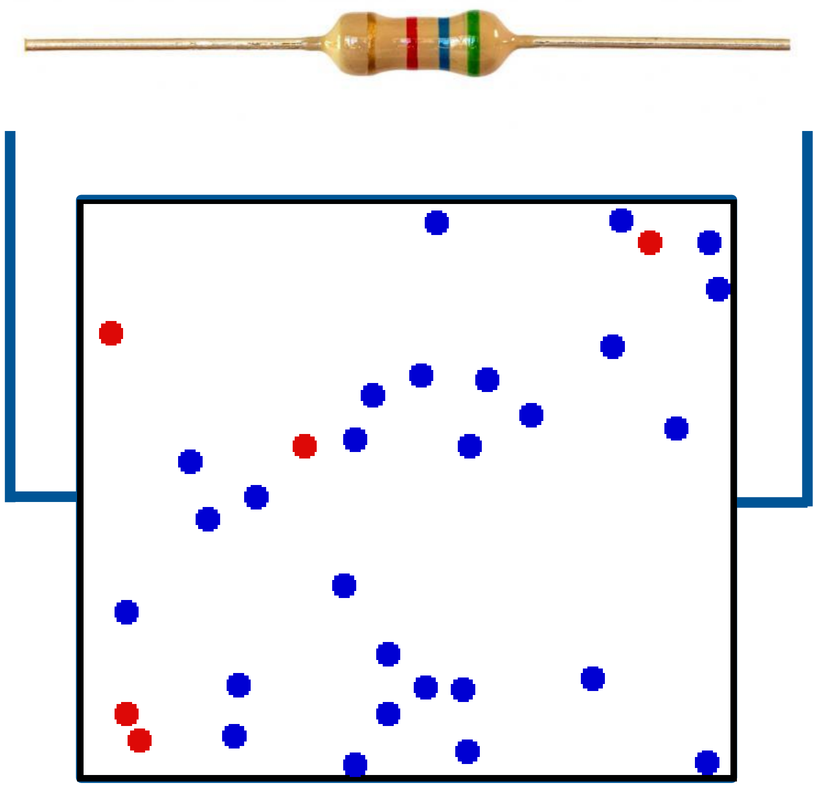
Next one on 5 May 2020 at AFRC, Glasgow

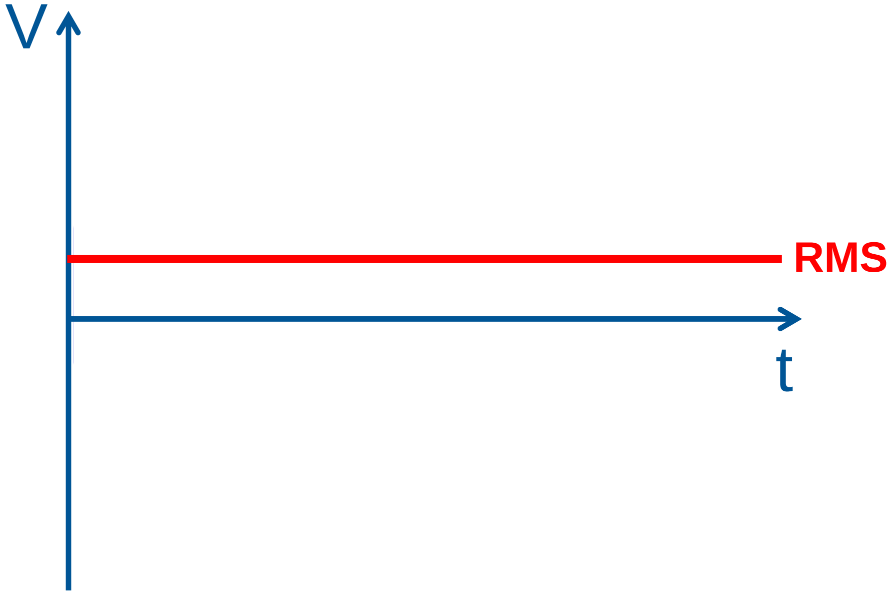
Speakers from:

- *Land Instruments,*
- *Otto-von-Guericke-Universität Magdeburg*
- *Tata Steel*
- *Heraeus Conamic UK*
- *CCPI Europe*
- *Metrosol*
- *Oxsensis*
- *University of Southampton*
- *University of Strathclyde*
- *Danmarks Tekniske Universitet*
- *Physikalisch-Technische Bundesanstalt*

- EMPRESS 2
  - Phosphor thermometry
  - Thermocouples
  - Combustion/flame thermometry
  - Fibre-optic thermometry
- Practical Johnson noise thermometry

Johnson noise thermometry





Same over all frequencies – white noise

$$\overline{V_T^2} = 4kTR\Delta f$$

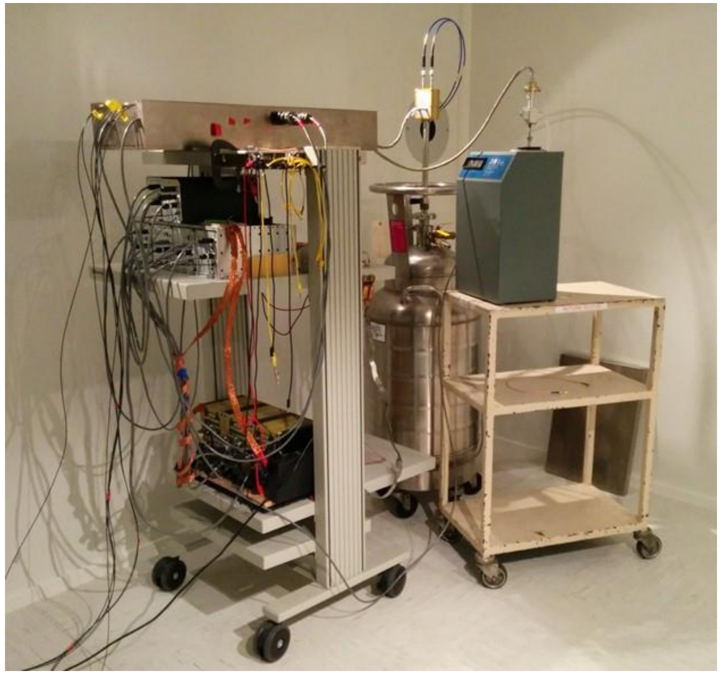
V_T: Johnson noise voltage
k: Boltzmann constant
T: temperature
R: resistance of sensor
Δf: frequency bandwidth

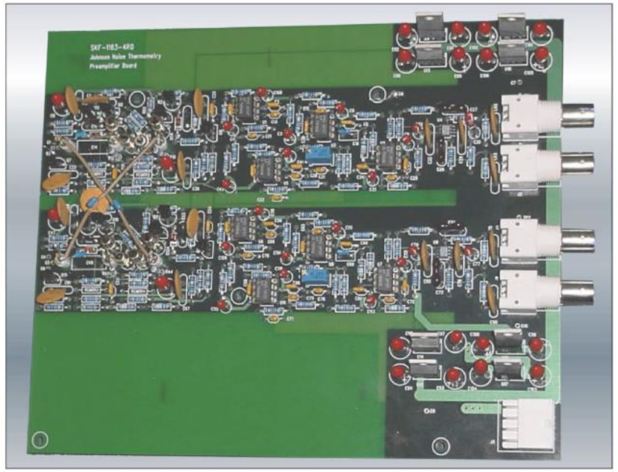
History

- Small signal, wide frequency band effect
- Some excellent JNTs out there – but sub-mK accuracy, not practical
- Brixy (Forschungszentrum Jülich) – successful, but slow and not commercialised
- Oak Ridge National Laboratory – didn't really work (but some really good ideas, and extremely well documented)
- Two main problems:
  - Very small signals
  - Difficult in determining the bandwidth

None have been commercialised

There are currently no other industrial thermometers based on Johnson noise

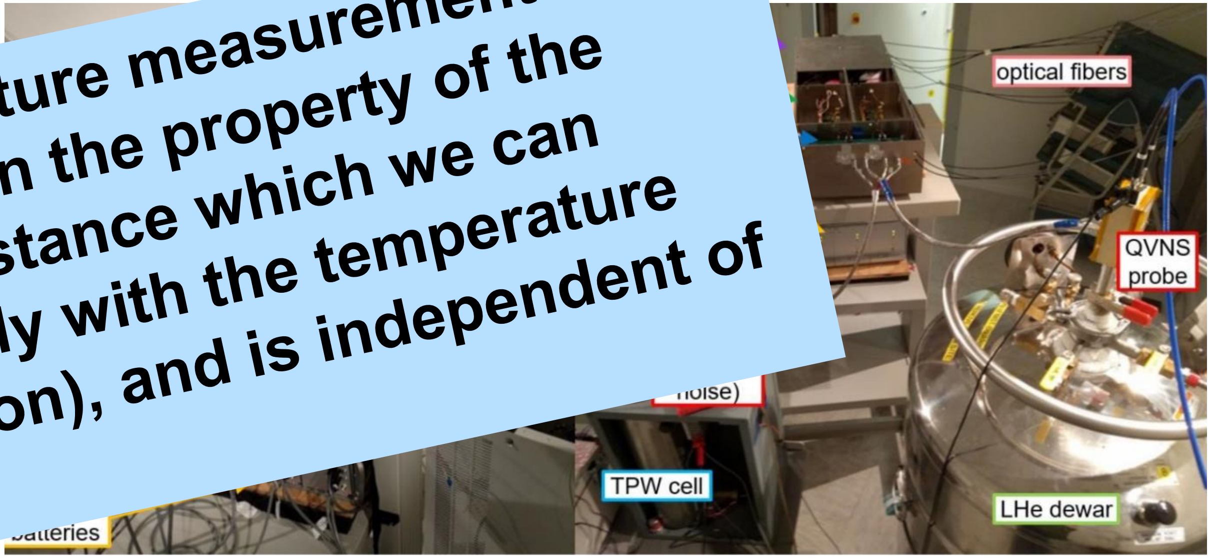


Background

- Metrosol & NPL
- Proof of concept
- Measure net voltage due to thermal movement of electrons – PRIMARY
- Linked to T through fundamental
- Accuracy ± 1 °C
- Doesn't need ca
- **All things that c environments a**
- So, no calibration
- *Tiny* voltage

Prior art: high cost, room sized experiments operating in a screened roo



Importantly, the temperature measurement is unaffected by changes in the property of the sensor (except the resistance which we can measure simultaneously with the temperature and apply compensation), and is independent of any calibration.

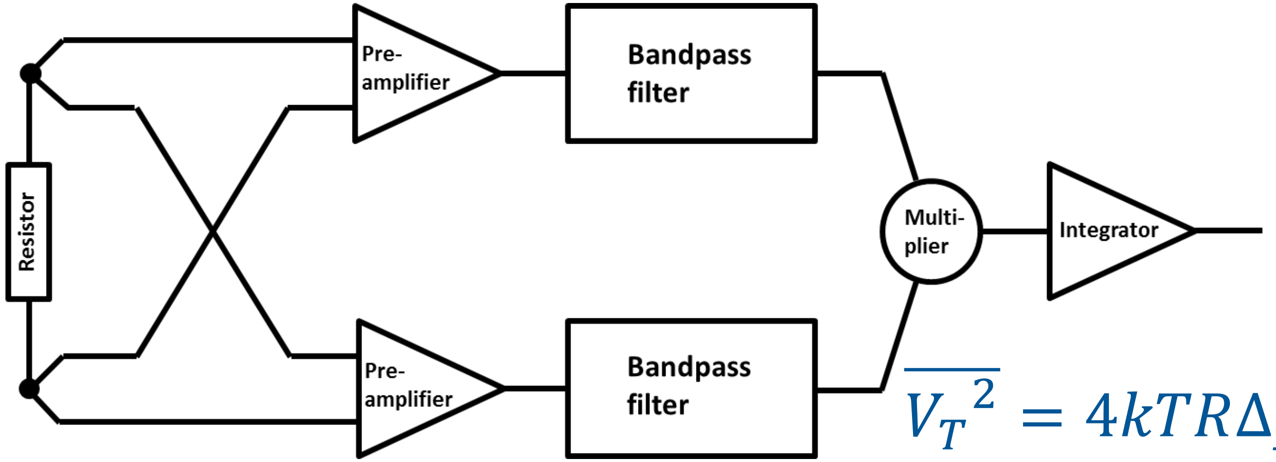
$$\overline{V_T^2} = 4kTR\Delta f$$

V_T: Johnson noise voltage
k: Boltzmann constant
T: temperature
R: resistance of sensor
Δf: frequency bandwidth

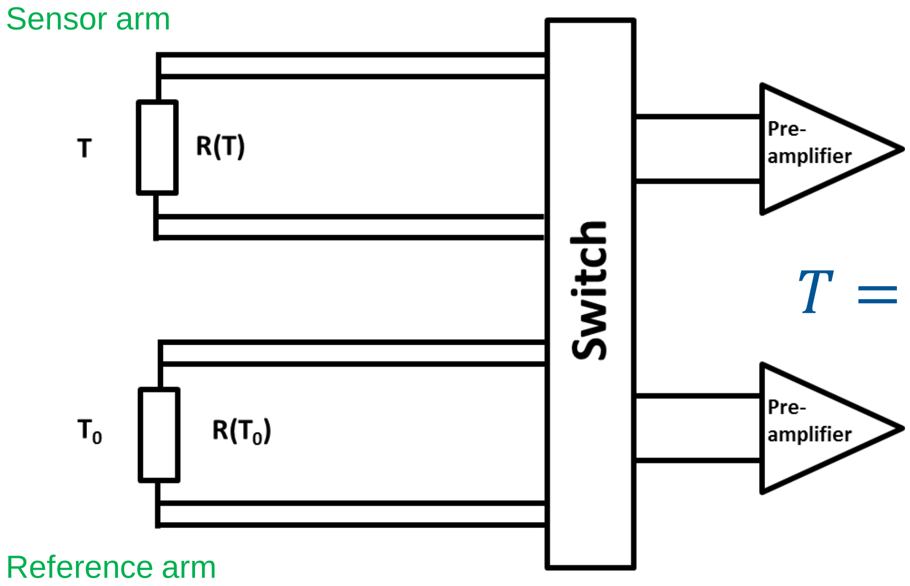
The key problems

- Correlation (amplifiers etc. introduce noise)
- In practice, can't measure bandwidth because frequency response is not rectangular: use Nyquist equation in ratio form ('substitution')
- Need a reference
- Need to switch between sense & ref resistor

- **Measurement time** – statistical effect
- **Component non-linearity** – frequency dependent attenuation of 'white' Johnson noise: *need to match bandwidths*
- Have to limit bandwidth so that measurement is on flat part of the frequency response
- Limits resistor to 100 Ω
- Limits the size of the Johnson noise signal
- ***Dependent on condition of cables – the very problem we want to avoid***



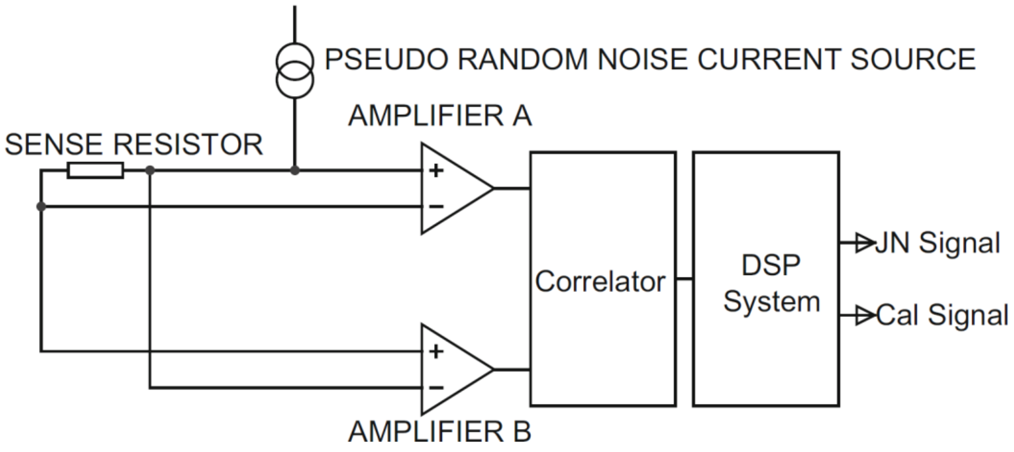
$$\overline{V_T{}^2} = 4kTR\Delta f$$

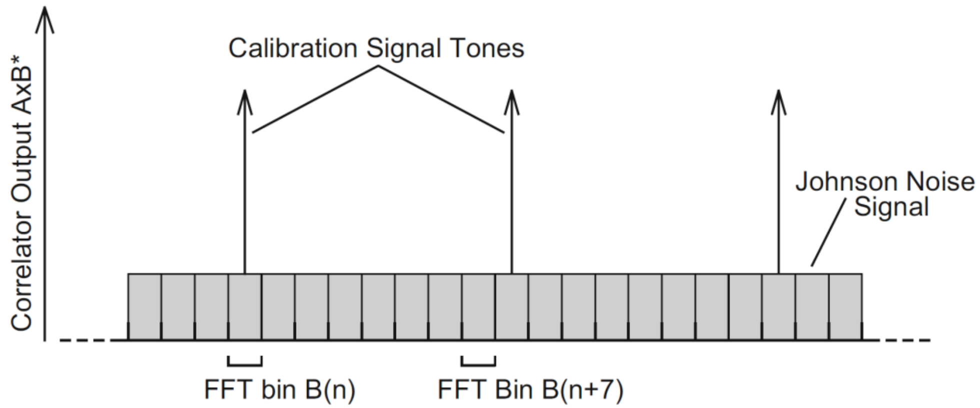


$$T = \frac{\overline{V_T^2}}{\overline{V_0^2}} \frac{R(T_0)}{R(T)} T_0$$

The topology: JNT1

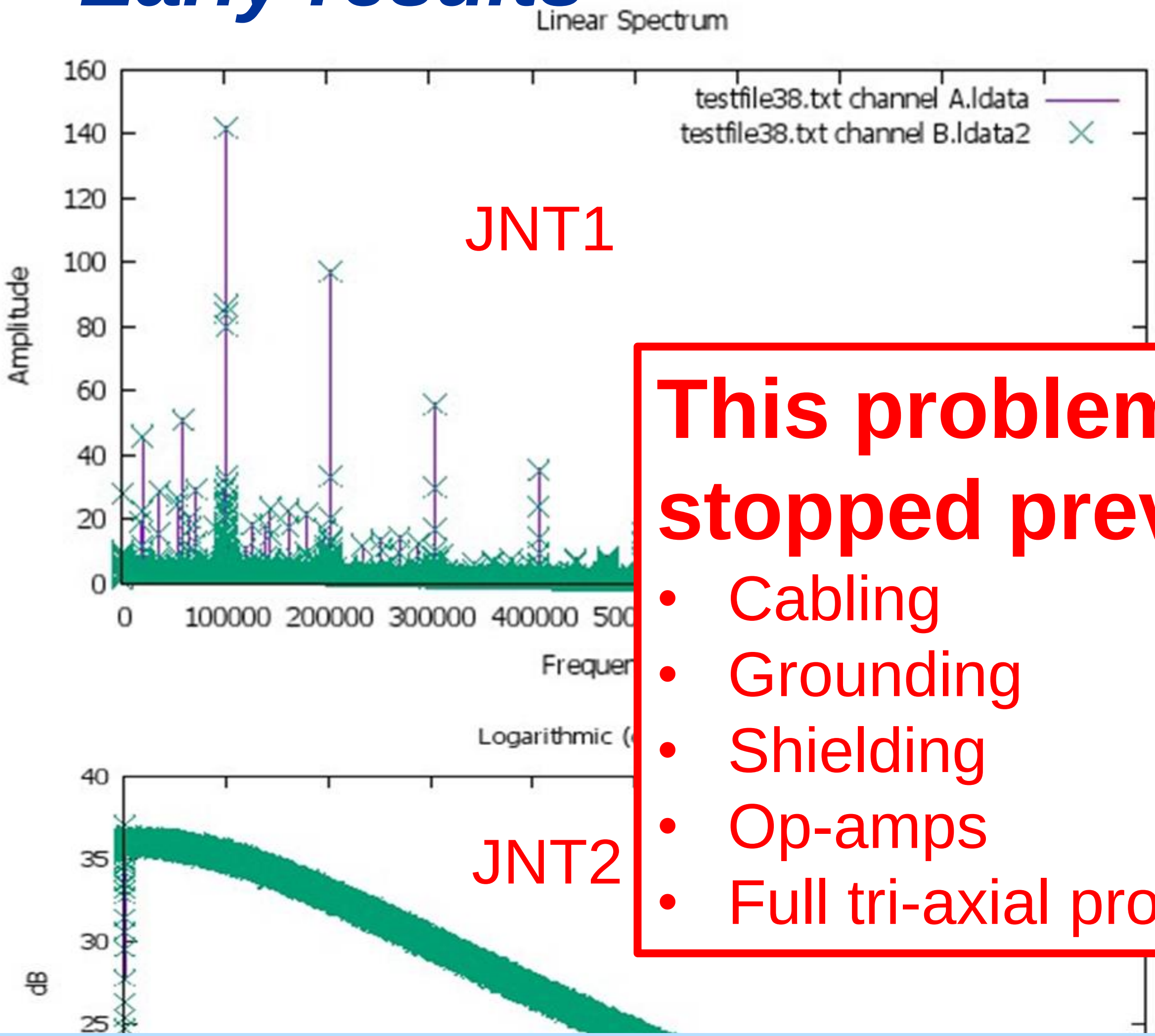
- Replace reference with pseudo-random noise source with calibration tones
- Requires no switching
- No need to match time constant of the two arms (there's only one arm) – better accuracy
- Tolerant of non-flat frequency response, since the two signals experience the same frequency response
- Can operate at much higher resistance (5000 Ω c.f. 100 Ω)
- And much higher bandwidth (1MHz c.f. 100 kHz)
- ***Factor of 1000 improvement in signal over previous attempts***





The measurement time of Metrosol JNT1 is about a factor of 20 faster than in previous attempts by others, at developing a practical Johnson noise thermometer

Early results



- **Passed industrial EMC testing**
- Radiated Field Immunity test to EN61000-4-3, 10 V m^{-1} 80-1000 MHz

to EN55011:2009

This problem has completely stopped previous efforts

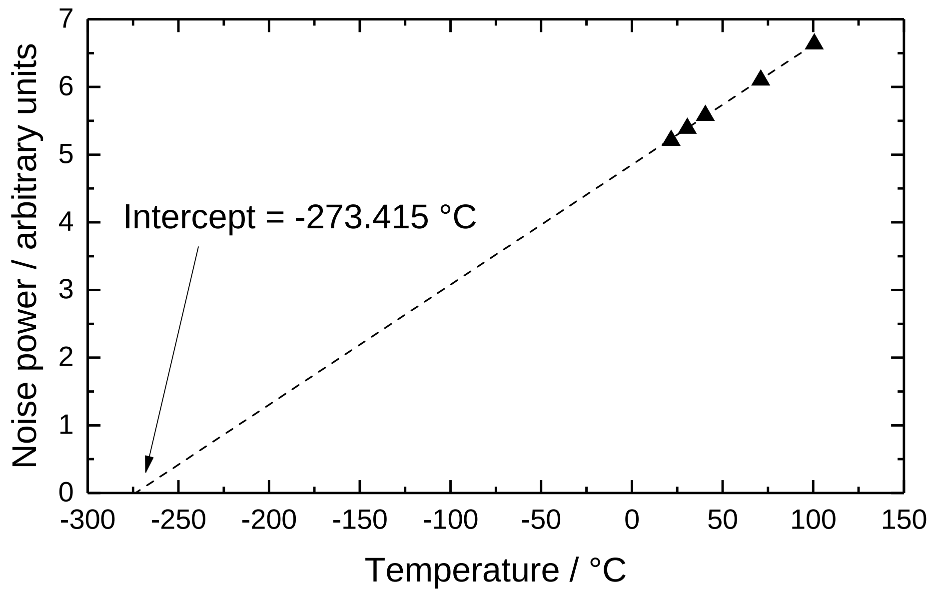
- Cabling
- Grounding
- Shielding
- Op-amps
- Full tri-axial probe connections

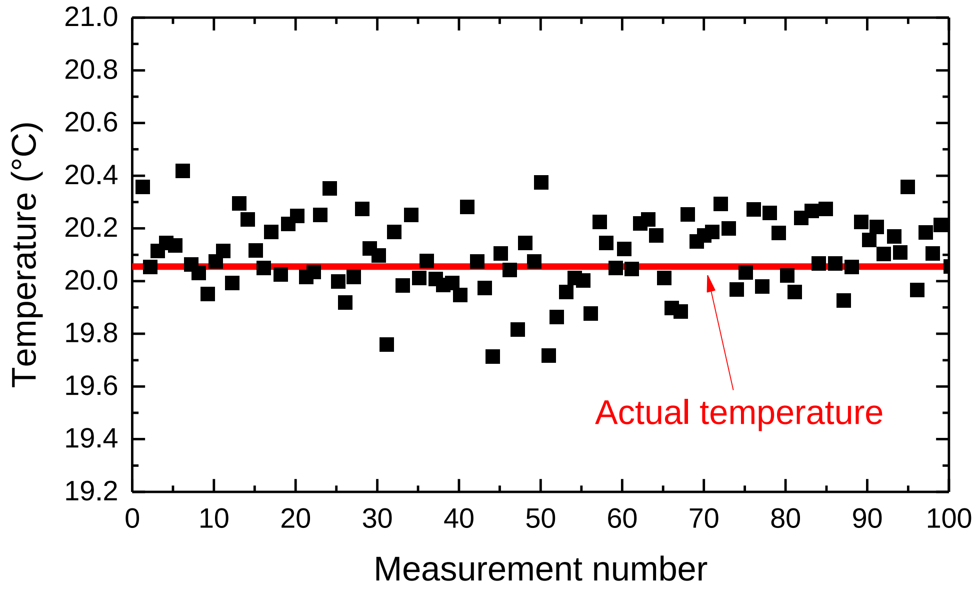
This level of EMC immunity had not previously been achieved and indeed this was one of the main reasons why previous attempts by others to produce a commercial JNT have not materialised.

Early results

- Standard deviation about 0.241 °C
- Target uncertainty about 1 °C over about 7 seconds
- Excellent EMC compatibility/immunity

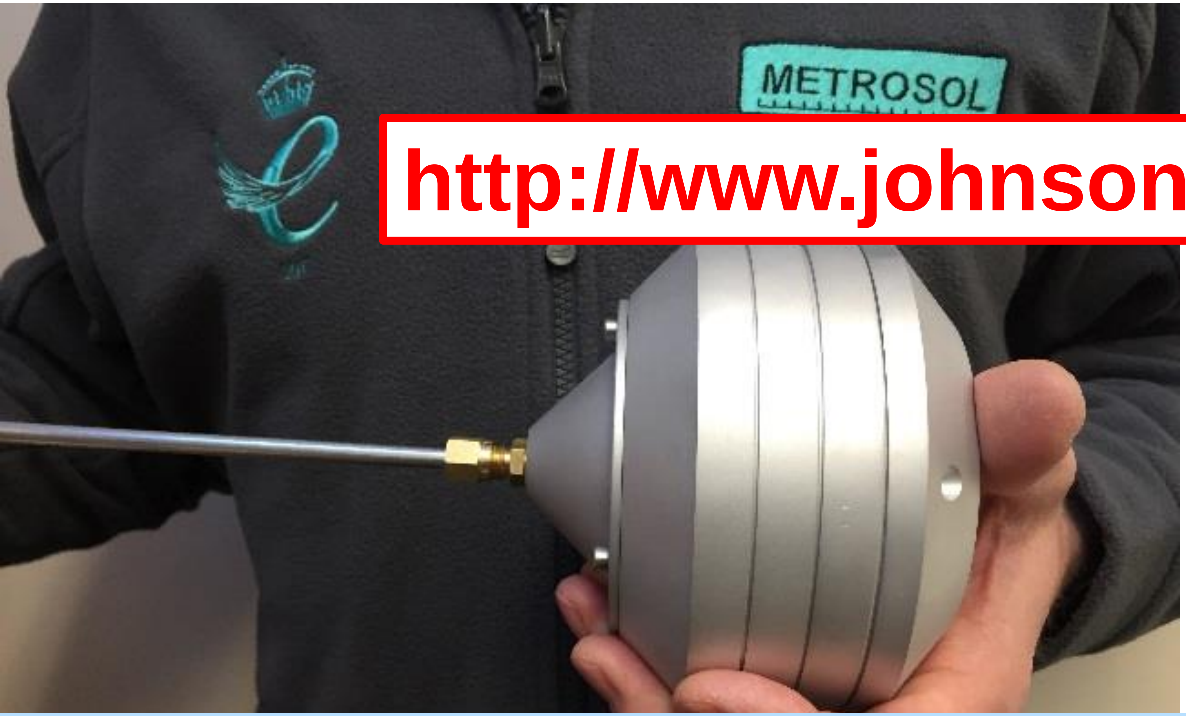
- Aim to start commercialising in 2020/21





Towards commercialisation – JNT 2

- More compact
- Superior EMI immunity
- On-board DSP
- FPGAs – available unlocked for specific applications (with suitable IP protection)
- On-board ADC identified



http://www.johnson-noise-thermometer.com

The second, more compact prototype JNT 2 is currently in development (programme runs to Q3 2020) to produce a JNT that is close to commercialisation.

- EMPRESS 2
  - Phosphor thermometry
  - Thermocouples
  - Combustion/flame thermometry
  - Fibre-optic thermometry
- Practical Johnson noise thermometry

Thank you!

Department for Business, Energy & Industrial Strategy

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The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

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