# Enhancing process efficiency through improved temperature measurement: the EMPRESS projects

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**Abstract**. EMPRESS 2 is a new European project to enhance the efficiency of high value manufacturing processes by improving temperature measurement and control capability. This project seeks to address four contemporary thermometry challenges in this sector, and new developments from this and its predecessor project, EMPRESS, will be described:

• Below 1000 °C many industrial processes require reliable surface thermometry e.g. welding, coating, forging and forming. Conventional non-contact surface thermometry techniques e.g. thermal imaging are prone to large errors (tens of degrees) due to reflected thermal radiation and unknown emissivity. Contact thermometry approaches are prone to similarly large errors. Traceable imaging phosphor thermometry is being developed to overcome these difficulties, and is being combined with quantitative thermography to determine emissivity for thermometry over wide fields of view.

• Above 1300 °C sensor drift is a significant unaddressed issue for casting, forging and heat treatment, causing large errors. There is a need for more stable sensors and standardisation of at least one new thermocouple type to fill the gap from 1300 °C to 1800 °C. This is being addressed through improved Pt-Rh thermocouples and optimisation of double-walled mineral insulated, metal sheathed thermocouples by mitigating insulation breakdown and drift effects.

• Combustion temperature measurement is very challenging and traceability is almost non-existent; for example, thermocouple measurements of flame temperatures can be in error by hundreds of degrees. A 'standard flame' that can be transported to users' sites has been developed, and is being deployed in several high value manufacturing and industrial applications to a) demonstrate the possibility of reducing flame temperature uncertainties by at least an order of magnitude and b) for the first time to demonstrate in-situ traceability to the International Temperature Scale of 1990 (ITS-90).

• Many processes are not amenable to any conventional thermometry techniques due to inaccessibility, ionising radiation, electromagnetic interference, and contamination; here methods based on optical fibres are ideal but there are no traceable calibration techniques for such sensors currently available. A suite of different fibre-optic thermometers and calibration techniques is being developed to address this. In some cases (ionising radiation) darkening of the fibre is a problem, and this is being overcome by the development of novel thermometry approaches based on practical 'hollow core' fibres.

## 1. Introduction

Manufacturing in the EU currently accounts for about 40 % of EU exports, and the lion's share of company R&D takes place in high value manufacturing [1]. However, the proportion of manufacturing has been in decline as services account for an increasing share of exports. The EU has strategic ambitions to restore a sustainable level of manufacturing and achieve or retain global leadership in sectors such as automotive, aeronautics, engineering, space, chemicals and pharmaceutical industries [2]. EU companies cannot compete on low price, low quality products. They must turn to innovation and productivity, energy and resource efficiency (and minimising waste), and high value-added to compete in global markets [3]. In practical terms this means enhancing efficiency – that is, energy efficiency and improved product consistency, which are strongly correlated – in industrial processes, which means improving process control, i.e. temperature measurement.

There is a practical imperative for European organisations: the EU's climate and energy package mandates a 20 % increase in energy efficiency across Europe by 2020 [4]. This is considered a Grand Challenge in EURAMET's Strategic Research Agenda for Metrology in Europe 2016 [5], which also identified the improvement of the efficiency of power generation and other industrial processes through improved metrology of critical monitoring and control parameters as a research priority [5]. Improved *in-situ* monitoring and control for enhancing process efficiency through improved instrumentation is identified in [5] as a key outcome. All energy efficiency gains are accompanied by a corresponding reduction in carbon emissions [6]. An energy efficiency improvement target of 20 % is also the aim of the European Directive 2012/27EU [7] on energy efficiency, which has recently been updated with an even more ambitious target of 30 % by 2030 in COM(2016) 860 [8] with a proposal for legislation in COM(2016) 761 [9]. This signals the intent of the EU to bring energy efficiency to the forefront of its strategy. The target of 30 % looks set to be formalised by a revision to Directive 2012/27/EU [9].

There are a number of key challenges in high value manufacturing associated with improving efficiency (i.e. both energy efficiency and improved productivity) and reducing greenhouse gas emissions. Surface temperature measurement is a common challenge in advanced manufacturing. Measurement of the temperature of billets during forming, forging and heat treatment up to 1000 °C remains problematic because contact probes cannot be inserted or placed in contact with the surface due to contamination and heat flow effects (which cause errors). Non-contact thermometry methods are beset by the problem of unknown emissivity and reflected thermal radiation. Heat treatment of steel structures before and after welding is a critical part of large scale manufacturing, and a rapid, practical means of measuring the surface temperature is urgently needed due to the very high rejection rates and poor product consistency associated with existing methodologies. Measurement of the surface temperature of rapidly moving parts e.g. automotive brake disks, which can reach up to 1000 °C, remains challenging due to the difficulty of ensuring that conventional contact probes are in adequate thermal contact with the surface. The use of phosphors has facilitated improvements in this area because they are effectively a coating which is in almost perfect thermal contact with the surface and it is non-perturbative, but they provide only a point measurement; what is really needed is an imaging technique to provide information on the spatial temperature distribution. Here traceable 2D phosphor thermometry will be developed, both with scanning techniques and by combination with quantitative thermography to solve the emissivity problem with conventional radiance based thermometry approaches.

The imminent introduction of a new double-walled MI thermocouple by UCAM and CCPI [10] will result in the commercial availability of a new ultra-stable thermocouple for use up to 1300 °C. However, the new double-walled format makes it challenging to meet the dimensional requirements set out in IEC 61515 [11] because the thicker protective outer wall reduces the amount of space inside leading to the thermocouple wires having a smaller diameter which in many cases falls below the minimum permitted by the standard. Similar limitations apply to industry standards such as AMS 2750E [12] (heavily used in aerospace manufacturing), which may limit uptake. Drift tests of the new thermocouples alongside conventional MI thermocouples are required to provide the documentary evidence needed to revise IEC 61515. To maximise the benefits to end users, further optimisation is required, in particular the optimisation of the ratio of the two outer wall thicknesses. Furthermore, now that these sensors exhibit substantially improved stability up to 1300 °C, a new measurement error has appeared, due to the decreased resistance of the insulating ceramic material between the thermocouple wires [13]. Also above about 1000 °C Pt-Rh thermocouples are increasingly widely used. In EMPRESS a systematic investigation identified the Pt-40%Rh vs. Pt-6%Rh thermocouple as being optimal in terms of stability; and a series of measurements are required to progress the standardisation of these developments. Essential underpinning standardisation measurements are needed.

Fire resistance testing and standardisation in aerospace applications remains a significant issue due to the extreme difficulty of measuring reliable and traceable flame temperatures; this generally requires the two dimensional measurement of flame temperature. Flame and combustion temperature in R&D production settings is often performed with sophisticated laser diagnostic apparatus; but, despite the sophistication, temperature uncertainties are typically of the order of 10 % and are not traceable. Measurements are often used to validate combustion models; more accurate modelling requires better measurements. A number of European companies are developing combined heat and power (CHP) plants and waste incinerators for both domestic and industrial use; widespread uptake of CHP is identified as a priority by the European Commission [14]. For small electricity/heat production units such as, for example, waste incinerators and/or district power plants, selective non-catalytic reduction (SNCR) technology is commonly used to reduce $NO_x$ emissions at around 1000 °C. A 2D temperature profile measurement of the combustion process will enable better control of the temperature in the $NO_x$ SNRC process, to optimise $NO_x$ reduction and consumption of $NH_3$/$NH_4OH$. A portable standard flame is needed to introduce traceability, to improve process control accuracy, and to enhance efficiency.

There are many processes (e.g. brake pad production/testing, forging) which strongly depend on temperature and which are not amenable to monitoring with conventional sensors such as thermocouples (contamination/transmutation/electromagnetic fields) or thermography (unknown emissivity/no line-of-sight). Examples include plasma-based processes, silicon processing, ionising radiation, particularly the gamma rays used for radiotracers or weld inspection, and high temperature industrial furnaces e.g. induction furnaces. Fibre-optic thermometers have become widespread since their inception in the 1960s, but few, if any, currently offer the possibility of traceable measurements. Different types of fibre-optic thermometers need to be developed offering immunity to different types of harsh environment, including point sensors and distributed sensors. Development of each type of sensor needs to be accompanied by the development of a traceable calibration methodology, and an *in-situ* demonstration in process environments in order to demonstrate the utility of the new metrological framework for fibre-optic thermometry.

This paper is laid out as follows. Firstly the EMPRESS2 consortium is introduced with a description of the partners’ activities and synergies. The technical activities are then summarised, with four work packages devoted to phosphor thermometry, thermocouples, combustion thermometry and fibre optic thermometry respectively. The paper concludes with a brief summary.

## 2. The consortium

The consortium comprises 26 partners across Europe including 9 NMIs, 2 DIs, 4 universities, 2 research institutes, and 9 companies. The partners are summarised in Table 1; this also shows the strong complementarity of the specialisms.

| Participant Type | Short Name | Organisation legal full name | Country | Specialism |
|---|---|---|---|---|
| NMI, Project Coordinator | NPL | National Physical Laboratory | United Kingdom | Thermocouples, fibre optics, phosphor, combustion |
| NMI | CEM | Centro Español de Metrología | Spain | Thermocouples |
| NMI | CMI | Český Metrologický Institut Brno | Czech Republic | Thermocouples |
| NMI | DTI | Teknologisk Institut | Denmark | Surface temperature |
| NMI | INRIM | Istituto Nazionale di Ricerca Metrologica | Italy | Phosphor thermometry |
| NMI | JV | Justervesenet | Norway | Optics, blackbodies |
| NMI | PTB | Physikalisch-Technische Bundesanstalt | Germany | Thermocouples, photonics |
| NMI | TUBITAK | Turkiye Bilimsel ve Teknolojik Arastirma Kurumu | Turkey | Thermocouples |
| NMI | UL | Univerza v Ljubljani | Slovenia | Thermocouples |
| DI | CSIC | Agencia Estatal Consejo Superior de Investigaciones Cientificas | Spain | Optical fibre thermometry |
| DI | DTU | Danmarks Tekniske Universitet | Denmark | IR & UV spectroscopy |
| Research institute | CNR | Consiglio Nazionale delle Ricerche | Italy | Tribology |
| Research institute | IPHT | Leibniz-Institut für Photonische Technologien eV | Germany | Fibre optics, lasers |
| Company | Elkem | Elkem AS | Norway | Silicon processing |
| Company | ITT | ITT | Italy | Braking systems |
| Company | MUT | MUT Advanced Heating GmbH | Germany | Furnace manufacturing |
| Company | ACERINOX | Acerinox SA | Spain | Steel manufacturing |
| Company | BAE | BAE Systems Marine Limited | United Kingdom | Shipbuilding |
| Company | B&W Volund | Babcock & Wilcox Vølund A/S | Denmark | Waste incineration |
| Company | CCPI | CCPI Europe Ltd | United Kingdom | Thermocouples |
| Company | JM | Johnson Matthey | United Kingdom | Precious metals |
| Company | Sensia | Sensia Solutions | Spain | IR imaging devices |
| University | UoS | University of Southampton | United Kingdom | Hollow core fibres |
| University | STRATH | University of Strathclyde (includes Advanced Forming Research Centre, AFRC) | United Kingdom | Phosphor thermometry & forming/forging |
| University | UC3M | Universidad Carlos III de Madrid | Spain | Optics & IR instruments |
| University | UCAM | The Chancellor, Masters and Scholars of the University of Cambridge | United Kingdom | Thermocouples |

**Table 1.** Project partners and their associated specialisms.

| Activity | Participant | Specialism |
|---|---|---|
| ***Phosphor thermometry (decay-time)*** | INRIM | Phosphor thermometry development |
| | CNR | Tribology |
| | ITT | Manufacture of braking systems |
| ***Phosphor thermometry (intensity ratio)*** | NPL | Phosphor thermometry development, traceable calibration techniques |
| | STRATH | Phosphor thermometry development |
| | DTI | Phosphor thermometry development |
| | BAE | Provide access to marine manufacturing for trials |
| ***Thermocouple thermometry*** | CMI, TUBITAK, UL, NPL, PTB, CEM, DTI | Traceable calibration facilities |
| | JM, CCPI, UCAM | Supply of thermocouple wire |
| ***Combustion thermometry*** | NPL | Supply, calibrate portable standard flame |
| | DTU | Development of IR, UV spectroscopy *in-situ*/on-line measurement techniques |
| | B&W VOLUND | Provide access to waste incineration facilities for trials |
| | SENSIA | Development of commercial IR imaging devices |
| | UC3M | Development of optics and IR instrumentation |
| ***Fibre-optic thermometry (hybrid BB/FBG)*** | IPHT | Development of laser and fibre optic techniques |
| | JV | Development of sapphire based sensors; traceable calibration techniques |
| | PTB | Development of FBG fibre optic sensors; traceable calibration techniques |
| | MUT | Provide access to industrial furnace manufacturing for trials |
| | Elkem | Provide access to silicon processing for trials |
| ***Fibre-optic thermometry (hollow-core/bundles)*** | UoS | Optical fibre development, instrumentation |
| | NPL | Development of traceable calibration techniques |
| ***Fibre-optic thermometry (distributed)*** | CSIC | Testing and development of fibre optic sensors |
| | ACERINOX | Provide access to stainless steel manufacturing for trials |
| | CEM | Development of traceable calibration techniques |

**Table 2.** Grouping of specialisms to illustrate the collaborative activities.

## 3. The work packages

Good progress was made in the first EMPRESS project [15,16], particularly in the development of working prototypes of several novel thermometers including the phosphor thermometer, several new types of ultra-stable thermocouples, a portable standard flame and a suite of flame and combustion temperature diagnostic techniques. In particular, each of the key developments was tested in at least one real-world setting. The activities are grouped into four work packages devoted to phosphor thermometry, thermocouples, combustion thermometry and fibre optic thermometry respectively.

### *3.1. WP1: Accurate methods for phosphor thermometry*

In the new project, EMPRESS2, phosphor thermometry will be further developed to facilitate reliable surface temperature mapping for the first time, so that parts undergoing forging, forming, welding, or heat treatment can be monitored with respect to the entire surface rather than a point. Secondly, the technique will be combined with quantitative thermography to enable real-time determination of emissivity, with a target uncertainty of better than 3 °C up to 1000 °C. Multiple partners, bringing complementary techniques, will enable validation of these techniques and implementation in-process in a suite of manufacturing environments.

In EMPRESS, traceable phosphor thermometry was established on a routine basis, with the phosphor coating being applied to a surface and a spot measurement made with uncertainty of about 1 °C. With this, surface temperatures up to 500 °C can be performed. The concept is being taken forward in EMPRESS2 with three aims in mind, namely to extend to 1000 °C, to extend to two dimensions, i.e. phosphor imaging, and to combine with quantitative thermography to enable in-situ determination of emissivity.

The aim of this activity is to develop, validate and test a suite of phosphor thermometry sensing techniques for accurate and traceable surface temperature measurement. The outputs will be trialled in high-value manufacturing processes, such as welding, coating, forging and forming, to provide traceable surface temperature measurements. The systems will be developed for use up to 1000 °C.
There are three key types of phosphor thermometry systems to be developed, each with a specific type of application in mind:

1. The first is a 2D intensity ratio phosphor thermometer, employing a traceably calibrated phosphor. This will be combined with quantitative thermography, enabling the production of emissivity maps.
2. The second will be optimised for the coating of billets to enable both online monitoring of billet temperature over the entire piece during heat treatment, and 'offline' monitoring whereby the phosphor records the temperature during the heat treatment for subsequent determination. The latter approach is useful when the billet cannot be viewed.
3. The third is a fibre-optic system for remote interrogation of the phosphor with a specific application in automotive brake pad/disk temperature determination. The target uncertainty of the techniques is less than 3 °C up to 1000 °C.

The following is a summary of the six key tasks.

#### *3.1.1. Task 1.1 Development of a phosphor thermometer from 500 °C to 1000 °C*

The aim of this task is to develop a phosphor thermometry capability up to 1000 °C and to demonstrate its performance in a number of trials. The accuracy of non-contact surface thermometry critically depends on knowledge of the surface emissivity. Additionally, background thermal radiation reflected from the surface can introduce significant measurement errors. Phosphor thermometry involves the interrogation of a thin phosphor coating (previously applied to the surface) following excitation from UV radiation. By measuring either the decay in the subsequent fluorescence with time or measuring the ratio of two emission bands, the temperature can be found that is independent of surface emissivity, background radiation and moderate levels of participating media between the surface and the instrument (i.e. windows, smoke etc.). By combining phosphor thermometry and established thermal imaging, it will be possible to independently determine the surface emissivity and to significantly reduce thermal imaging uncertainties (to an uncertainty better than 3 °C).

**Progress:** NPL has developed a prototype intensity ratio imaging phosphor thermometer that can measure from 20 °C to 450 °C [17]. This has been applied to a real-world measurement problem, namely a 3 mm x 1 mm x 20 mm steel coupon electrically heated in the NPL electro-thermal mechanical testing (ETMT) machine. Although the coupon is behind a Perspex cover, unlike thermography (thermal imaging), the phosphor thermometry is unperturbed by the cover, and, also unlike thermography, information on the emissivity is not needed. Figure 1 shows a typical 2D image of the coupon made with the new system.

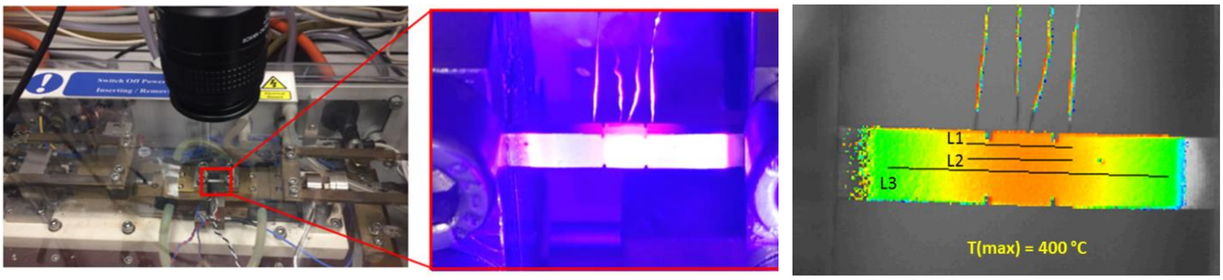


**Figure 1.** Phosphor thermometry applied to a coupon undergoing mechanical testing. Left: the testing apparatus, with the coupon shown in the box. Centre and right: temperature distribution (shown by colour) of the coupon.

Progress to the target temperature of 1000 °C will be challenging: phosphor and binder selection, and coating methods, for use at the highest temperatures are currently being considered. Ultimately the thermometer will be validated by performing traceable calibration up to 1000 °C, using either fixed points or by employing thermal validation targets (metal coatings with defined melting temperatures developed in EMPRESS). It is envisaged that combined 2D phosphor/thermal imaging measurements will be demonstrated to determine surface emissivity maps of at least two independent materials e.g. alloys supplied by STRATH. A similar activity will be performed with a spot pyrometer / phosphor thermometer (i.e. a point measurement).

The coatings are capable of being sprayed with thicknesses of around 35 μm while remaining durable and homogeneous. Additionally, if larger signal intensities are required the coatings can be applied thicker. Point measurements are currently achievable reliably, as the work carried out in EMPRESS demonstrated [15], although this was carried out at lower temperatures from about 20 °C to 200 °C. A new phosphor that works at higher temperatures e.g. $Y_2O_3$:Eu will be substituted. This can operate over the desired 500 °C to 1000 °C range, and offers a precision of better than 3 °C. It will operate using an intensity ratio technique currently operating with a dual camera setup, which is being developed. Other potential phosphors are YAG:Tb, $ScPo_4$:Eu and $GdAlO_3$:Tb.

*3.1.2. Task 1.2 Development of phosphor sensors for surface temperature monitoring on forging tools*

The aim of this task is to devise a phosphor sensor that is suitable for monitoring surface temperatures on the surfaces of forging tools up to 1000 °C. Tool temperature is critical for the quality of the components produced, but it is difficult to monitor due to the extreme conditions at the tool surface (high temperature, high mechanical loads and the presence of lubricants) and intermittent access (optical access can only be gained when the press is open between operations, whilst the temperatures experienced during the pressing process are the most critical). Phosphors operate at high temperatures, offer good signal to noise ratio and emissivity independent measurement, so they have the potential to meet the needs of this extreme environment. Two sensors can be envisaged. One for tool temperature monitoring on a continuous basis between every pressing operation and one for use during the setup of the apparatus, prior to actual processing, to record the surface temperature during the process when the tool is closed. The former can be achieved using an online sensor and the latter by an offline 'memory' type sensor. The task will seek to identify and characterise a suitable phosphor for each type of application.

**Progress:** STRATH has identified suitable phosphors with measurement capability in the relevant temperature range experienced by tools and work pieces in representative forging processes. This includes those phosphors with both on-line (i.e. live measurements) and off-line (i.e. inaccessible during the process – data is recovered afterwards) response modes. Using a selected phosphor a coating-type sensor design has been devised for on-line surface temperature mapping, and prototypes have been manufactured. A measurement system based on 2D lifetime decay mapping has been designed and is under development. Appropriate measurement systems including detectors and signal processing routines are also under development. Ultimately both systems will be tested and calibrated to determine the dynamic range and measurement uncertainty (target 3 °C). A three-gate technique has been identified that allows for the use of a single camera for surface phosphor thermometry and data analysis methods are under development.

*3.1.3. Task 1.3 Fibre-optic based measurement system for temperatures of up to 1000 °C in a braking system*

The aim of this task is to exploit a phosphor-based approach to develop a novel remote fibre-optic thermometer system, in order to provide traceable measurements in selected applications in the automotive industry for braking system development. The temperature at the contact surface of the disk and the brake pad during operation impacts significantly on brake performance, yet its measurement is very difficult. It can range between 400 °C and 1000 °C depending on the brake features. Temperature measurements, generally performed by using thermocouples inserted in the brake itself, are very complex and exhibit poor reliability. In contrast, analytical or numerical mathematical methods, often used to predict the brake temperature in the contact zone of the friction pair, typically requires numerous simplifications and restrictions in order to offer solutions to the observed problem. The phosphor-based fibre-optic thermometer system will address these issues.

**Progress:** INRIM has selected the phosphors to be used for thermometry up to 700 °C. A suitable high temperature ceramic binder, to be mixed with phosphor powder was also considered in order to obtain a robust, optically transparent and thin surface coating for different types of automotive brake pads. ITT and CNR will advise INRIM on practical constraints for specific industrial applications and at least one phosphor will be selected after evaluating the thermal sensitivity, optical and mechanical characteristics in light of the specific industrial application. INRIM will perform a traceable calibration of the selected phosphor in an isothermal environment by measuring its decay time at a series of known temperatures (at least two) over the whole working temperature range [18]. A standalone system, including an electro-optical unit, signal processing and software for measuring the fluorescence decay time as a function of temperature will be developed at INRIM. Preliminary functionality tests will be carried out before it is used in industrial applications. ITT will advise on practical aspects.

Different parameters have been considered such as functionality temperature range, fluorescence lifetime, thermal sensitivity, signal to noise ratio and optical features. Two phosphors were eventually selected: Chromium-doped $YAlO_3$ (Cr:YAP) and Cr-doped gadolinium aluminum perovskite (Cr:GAP). Cr:YAP exhibits a high temperature sensitivity over a wide working range (i.e. from 10 ms / °C to almost 100 ms / °C from room temperature to more than 700 °C), a high intensity of the fluorescence signal and a long fluorescence lifetime.

Cr:GAP is a phosphor that combines the ultra-bright luminescence of transition metal dopants with long decay-times even at high-temperatures; it is basically suitable for temperature measurements higher than 250 °C, but is more sensitive at temperatures above about 750 °C. A suitable high temperature ceramic binder, to be mixed with the phosphor powder, was also selected and several tests with different phosphor/binder ratio have been performed on the different type of surfaces in order to obtain adequate adhesion and uniformity of the phosphor coating.

A dedicated electro-optical system, suitable for the chosen phosphors, for the excitation and detection of the fluorescence lifetime has also been designed. Furthermore, Cr:YAP was also subjected to a preliminary calibration in a furnace in the range from room temperature to 600 °C.

*3.1.4. Task 1.4 In-process tests of a phosphor thermometer*

The aim of this task is to deploy the instrumentation developed in Task 1.1 (fibre-optic phosphor thermometer) under real operating conditions at STRATH (AFRC, heat treatment) and BAE (welding pre-heat treatment).

NPL will demonstrate precision phosphor thermometry of billets during heat treatment at STRATH (AFRC) and will compare the results with conventional thermal imaging techniques. NPL will demonstrate and test the 2D intensity ratio phosphor thermometry system in a number of marine welding applications in-process at BAE. NPL will demonstrate the phosphor thermometer/thermography combination in an industrial environment e.g. glass manufacturing at collaborator AGH. DTI will facilitate access to the collaborator's site.

#### *3.1.5. Task 1.5 Testing phosphor thermometry in a forging process*

The aim of this task is to test the phosphor thermometer systems developed at STRATH under real operating conditions in one of the heat treatment facilities at STRATH (AFRC).
STRATH will modify at least two selected forging tools to incorporate at least one of the selected phosphor sensors devised by STRATH. Multiple tool sets will be used to enable both online and offline sensors to be tested.

#### *3.1.6. Task 1.6 Phosphor thermometry applied to brake pads*

The aim of this task is to study the influence of temperature, as measured at the interface of an automotive brake pad and disk by phosphor thermometry, on braking system properties. Good performance of a braking system is strictly dependent on the formation of a so-called friction layer or third body, which forms when a disk and pad come into contact during braking. The heat generation during braking affects the topology of the friction layer. This in turn induces phenomena such as material deformation that changes the contact pressure, whose uneven distribution is the main reason for uneven wear. The measurement of the temperature at the interface is therefore an aspect of paramount importance when forecasting the whole performance of a braking system.

INRIM will develop an appropriate binding mechanism for good adhesion of a thick layer of the phosphor on at least one of the types of brake pad that is used in industrial applications (supplied by ITT). CNR will advise on binder property constraints. The phosphor thermometer developed by INRIM will be applied to the measurement of surface temperature in the brake testing rig at ITT's industrial facilities.

The surface of the pads and/or disks tested will be analysed by CNR, in order to evaluate the friction layer formed, if any, and any changes in terms of composition, leading to potential material degradation. As the thickness of tribologically induced films is usually of the order of 1 μm or thinner, surface techniques will be preferred. The analysis will either be carried out on both the pad and the disk or only on the disk, depending on the complexity of the pad composition chosen by ITT. SEM-EDS will be used by CNR to determine the morphological and elemental composition, on both the surface and cross section of the worn materials.

### *3.2. WP2: Low-drift thermocouples*

In EMPRESS, a systematic investigation of a number of different Pt-Rh thermocouples showed that the most stable thermocouple consistent with readily available Pt-Rh wire compositions, at least in the temperature range 1324 °C to 1492 °C, is the Pt-40%Rh versus Pt-6%Rh thermocouple [19-21]. A preliminary reference function was also drafted (Figure 2) [19]. In EMPRESS2, to facilitate uptake of the new thermocouple type, NMIs will systematically determine its reference function. This builds on the development of high temperature fixed points [22] in FP5 project G6RD-CT-2001-00610 HIMERT [23], EMRP JRP IND01 HiTeMS [24] and EMPIR JRP 14IND04 EMPRESS [25]. The utility of the optimised thermocouple will be demonstrated by trials in industrial furnace manufacturing, steel manufacturing, and other trials at collaborators' sites e.g. float glass manufacturing applications.

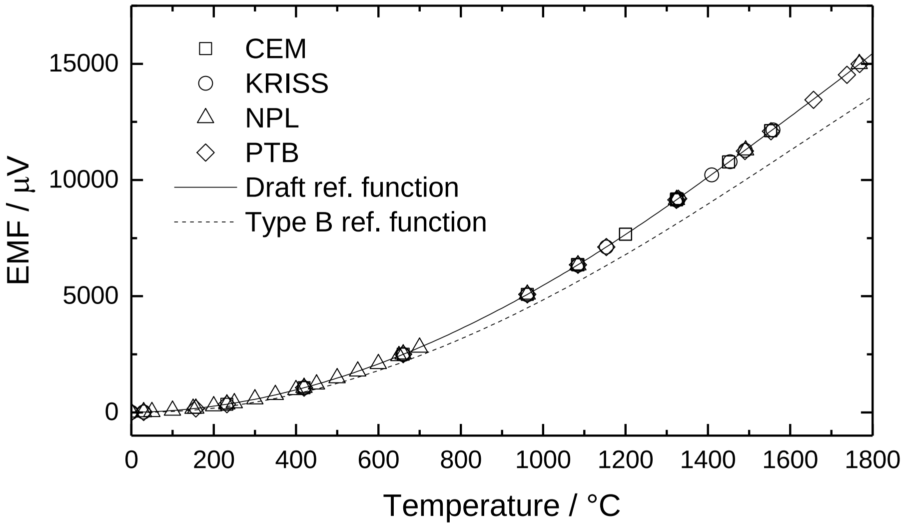


**Figure 2.** Preliminary reference function for the Pt-40%Rh vs. Pt-6%Rh thermocouple showing aggregated calibration data arranged by participant. The solid line shows the preliminary reference function; dashed line shows the Type B thermocouple reference function for comparison.

A second part of the thermocouple activities concerns the double-walled mineral insulated, metal sheathed (MI) thermocouple developed by UCAM [10]. This is currently the subject of a collaboration between UCAM and CCPI aimed at commercialising the new MI thermocouple type, which exhibits thermoelectric stability approaching that of noble metal thermocouples, at least up to about 1200 °C [10]. Some validation of the drift performance of Type K and Type N thermocouples with this format was performed by UCAM (Figure 3), and in an industrial vacuum furnace at AFRC in EMPRESS (Figure 4); further validation is urgently needed and will be undertaken by several NMIs. This will include a systematic optimisation of the wall geometry, specifically a determination of the optimum ratio of the two wall thicknesses. Finally, the progressive breakdown of the insulation resistance above 600 °C, as the ceramic becomes conductive, will also be studied; this is a potential problem for end-users since the new MI thermocouple is more stable and hence can be expected to be used at higher temperatures more regularly.

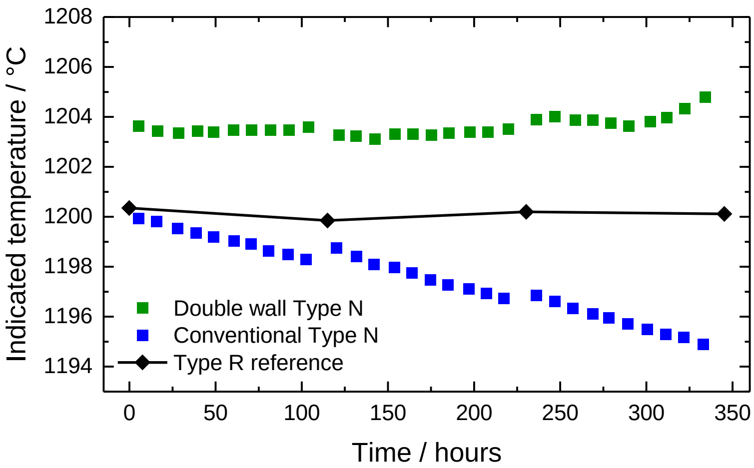


**Figure 3.** Comparison between the drift of 3 mm double wall Inconel 600 sheathed Type N thermocouples and the conventional equivalent during cycling between room temperature and 1200 °C.

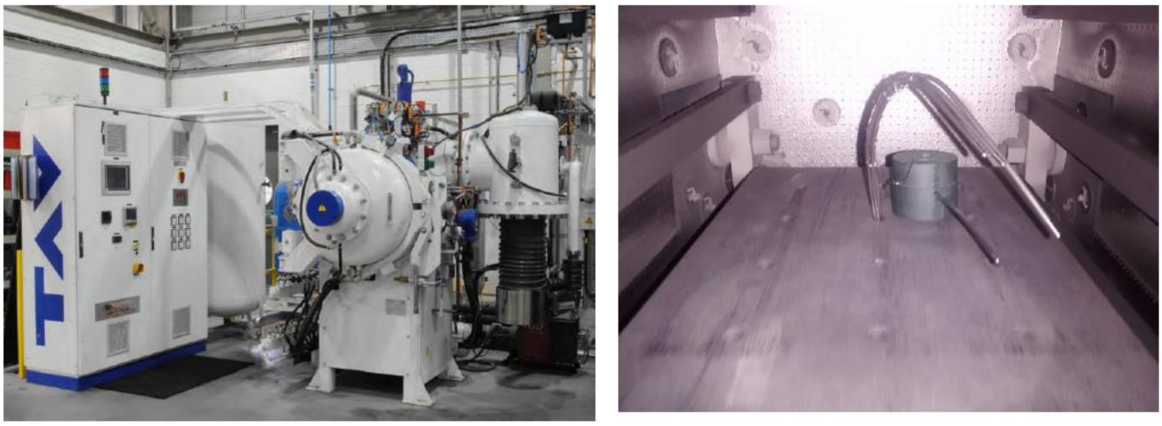

**Figure 4.** The industrial vacuum furnace at AFRC used for trials of the double-walled MI thermocouples (left) and the thermocouples installed in the furnace (right).

The objective is to characterise these novel thermocouples metrologically with in-process, traceable uncertainties of better than 3 °C for the new Pt-40%Rh vs. Pt-6%Rh thermocouples at temperatures up to 1769 °C and for the double-walled MI thermocouples at temperatures up to 1200 °C, as well as the insulation resistance breakdown. There are three key tasks:

#### *3.2.1. Task 2.1 Standardisation of Pt-40%Rh vs. Pt-6%Rh thermocouples*

The aim of this task is to establish an emf-temperature reference function for Pt-40%Rh vs. Pt-6%Rh thermocouples in the temperature range between 0 °C and 1769 °C in air. This will be based on a set of at least 5 (of 11 investigated) exceptionally thermoelectrically stable and homogeneous thermocouples. All required emf measurements will be traceable to the International Temperature Scale of 1990 (ITS-90) [26], based on measurements of the emf at fixed points and in comparison. The thermocouples will be constructed by the partners. Additionally, the post-assembling heat treatment will be optimised to reach the most stable thermoelectric conditions of the Pt-40%Rh vs. Pt-6%Rh thermocouples. The aim is to reach an expanded uncertainty of the emf-temperature reference function of less than a temperature equivalent of 0.5 °C up to 960 °C, rising smoothly to approximately 2 °C at 1769 °C.

Eleven Pt-40%Rh vs. Pt-6%Rh thermocouples have been constructed by PTB, NPL, CEM, CMI and TUBITAK by using thermoelements which have been provided by JM, and additional thermocouples provided to UL and DTI. These are now being used in the reference function determination. In particular, an agreed post-assembly heat treatment has been performed by PTB, CEM, CMI, NPL and TUBITAK to achieve a unique and thermoelectrically stable condition for all thermocouples. PTB and NPL have jointly prepared a measurement protocol to unify the pan-European measurement effort.

Using the facilities of PTB, NPL, CEM, CMI, DTI, TUBITAK and UL traceable measurements to ITS-90 are being performed at, where available, all ITS-90 fixed points and high temperature metal-carbon eutectic fixed points, and by applying comparison methods in the temperature range between 0 °C and 1769 °C in order to yield a large number of emf-temperature pairs. During these measurements, tests of the thermoelectric stability and homogeneity will be performed repeatedly according to the agreed measurement protocol.

**Progress:** So far, ten of the eleven thermocouples met the specified stability requirements (drift rate at the Cu point (1084.62 °C) less than 0.5 µV within 50 hours annealing at 1350 °C). The first set of calibrations of the Pt-40%Rh vs. Pt-6%Rh thermocouples in the temperature range from 0 °C to 420 °C (fixed points and comparison calibrations) are finished at PTB (two thermocouples), NPL (two thermocouples), and UL (one thermocouple). The third remaining thermocouple of PTB is currently undergoing long-term annealing at 1350 °C with intermediate test measurements at the freezing point of Cu to check the thermoelectric stability and homogeneity tests at 400 °C in a salt bath.

There will be a number of trials of the Pt-40%Rh vs. Pt-6%Rh thermocouples in industrial conditions e.g. float glass manufacturing to 1550 °C in Denmark. PTB will lead trials in industrial furnace manufacturing at MUT, and CMI will lead trials in a steel manufacturing facility to demonstrate the achieved stability of the thermocouples and the validity of the new emf-temperature reference function.

#### *3.2.2. Task 2.2 Optimisation of the stability of double-walled MI thermocouples up to 1200 °C*

The aim of this task is to optimise the design of double-walled MI thermocouples and to establish the basis for the standardisation of the double-walled MI thermocouples of types K and N. Comparison tests will be executed using double-walled MI thermocouples to find an optimal inner to outer wall thickness ratio. 60 further double-walled MI thermocouples, with the most promising inner to outer wall ratio, will be constructed and investigated in comparison with conventional MI thermocouples of the same type. The results will provide the basis for approaching standardisation bodies which will open up the opportunity to use the sensors widely in industrial applications.

Firstly, CCPI, with UCAM’s cooperation, will manufacture a cohort of double-walled MI thermocouples with 3 different inner to outer wall thickness ratios, including types K and N, with Inconel 600 sheaths and an outer diameter of 3 mm. NPL and UL will manufacture two Fe-C high temperature fixed point cells (1153 °C) to be used for drift testing. A series of drift tests on a wide selection of the cohort will be performed by PTB, CEM, CMI, NPL, TUBITAK and UL. Furthermore the influence of different electrical and magnetic fields on the operation of the double-walled MI thermocouples will be investigated by UL on at least two thermocouples, simulating everyday industrial use.

**Progress:** The manufacturing of the ‘standard’ version of the cable to construct the double-walled MI thermocouples has started. These double-walled MI thermocouples, as well as conventional single-walled MI thermocouples, will be provided to the partners for stability testing according to an agreed protocol. The cell design for the first high temperature fixed point was agreed by NPL and CEM: the length will be 79 mm, outer diameter 23 mm and the re-entrant well inner diameter 5.4 mm. The second cell has a different length of 40 mm and a diameter of 30 mm, according the UCAM conditions.

#### *3.2.3. Task 2.3 Assessment of the insulation resistance breakdown of MI thermocouples up to 1200 °C*
The aim of this task is to investigate the issue of insulation breakdown for MI thermocouples and to perform measurements of the insulation leakage of double-walled and conventional MI thermocouples of types K and N. There is evidence that, under particular conditions, conventional thermocouples experience insulation resistance breakdown at high temperatures. With operation at higher temperatures, less insulation between the thermoelements, and for the longer times that double-walled thermocouples allow, it is envisaged that the insulation material in the double walled thermocouples could experience resistance breakdown even more frequently. Measurement schemes will be devised to improve the characterisation of this effect by UCAM, CCPI, NPL and CEM.

#### *3.2.4. IEC 61515*
A key task is to provide evidence to the IEC committee TC 65/SC 65B/WG5 responsible for the MI thermocouple standard IEC 61515 [11] that the stability of double-walled MI thermocouples is superior to that of conventional single-walled thermocouples. A further difficulty with compliance of the double-walled MI cables with the IEC 61515 standard is the reduced cross-sectional area within the thermocouple due to the thicker wall. This means there is less space for the thermoelements which impedes compliance with the geometrical specifications. Evidence of superior stability, even with reduced thermoelement size and spacing, is needed before modifications to the geometrical requirements of IEC 61515 can be proposed.

### *3.3. WP3: Demonstration of a validated in-situ combustion reference standard*
In EMPRESS a portable standard flame was developed. By having a very well characterised gas composition and a judiciously designed geometry, the flame has a stable, spatially uniform temperature profile, and can be transported to end-users' sites to validate flame and combustion thermometry apparatus.

The flame system has been fully commissioned and is available as a measurement service to external customers. Using laser Rayleigh scattering, it has been possible to determine the post-flame temperature with an uncertainty of less than 0.5 % of temperature – this is a factor of two less than the original target uncertainty of 1 % of temperature. The flame and laser interrogation system are shown in Figure 5. Additionally, the system can provide a number of fixed and reproducible temperatures and species concentrations for propane/air equivalence ratios from $\phi = 0.8$ (lean flame) to $\phi = 1.4$ (rich flame). The range of (fixed) highly uniform temperatures that can be attained (dependent on $\phi$) is between 2050 K and 2250 K. This provides a robust mechanism to not only validate third party optical techniques but also assess their linearity. Measurements made by UC3M/CEM using a hyperspectral imager show excellent agreement with the standard portable flame (Figure 6), validating the technique and leading the way for development of a low-cost instrument in EMPRESS2. Measurements made by DTU using IR/UV spectroscopy are equally impressive, showing outstanding agreement with the NPL measurements. Additionally, comparison of the measured and modelled IR emission spectra by DTU allowed further improvement of the temperature profile characterisation performed by NPL. This demonstrates the value of collaborating on this type of activity. Figure 6 also shows the reproducibility of the flame temperature as measured after each journey to the partners' laboratories. Figure 7 shows the FTIR hyperspectral imaging system results at UC3M, which yields both temperature and density of individual species.

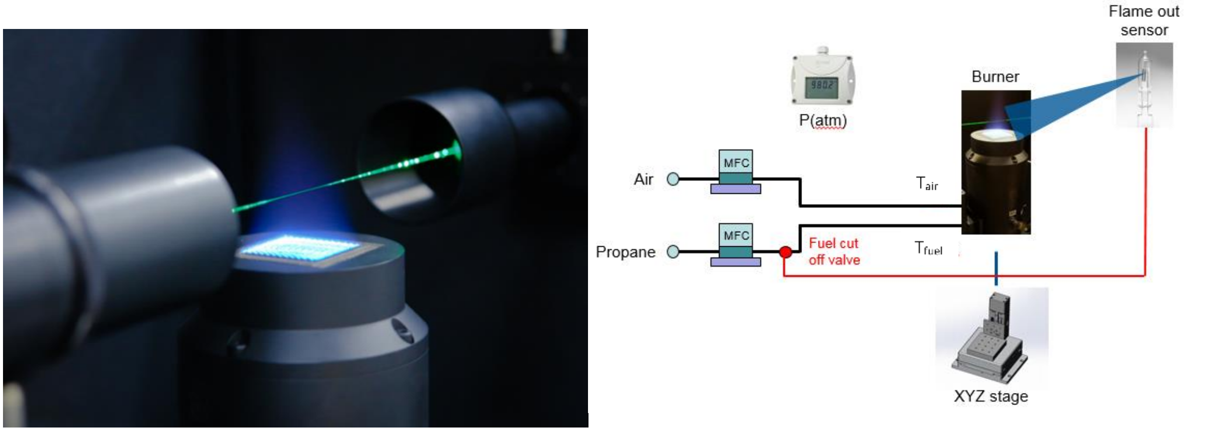


**Figure 5.** Left: Portable standard flame being interrogated by the laser Rayleigh scattering apparatus. Right: The gas metering and burner control system.

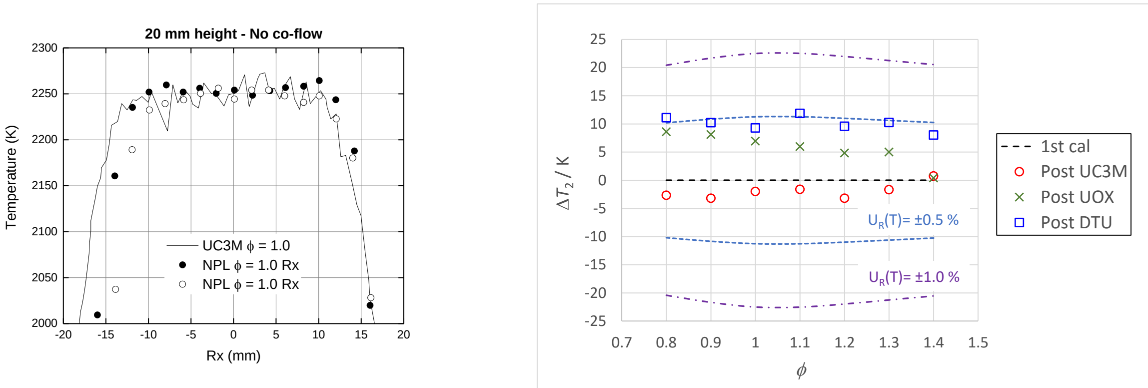


**Figure 6.** Left: Comparison of the spatial flame temperatures measured by NPL (Rayleigh scattering) and UC3M/CEM (hyperspectral imaging). Right: Shift in flame temperature as a function of ϕ following measurement campaigns at UC3M, UOXF and DTU.

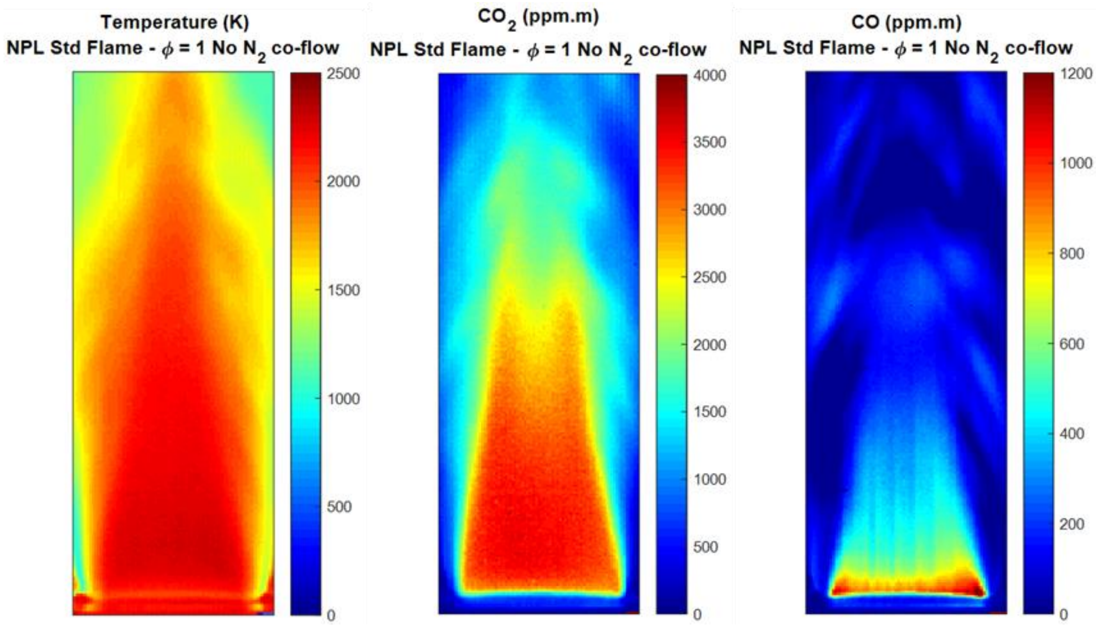

**Figure 7.** Temperature (left) and column density maps (middle – $CO_2$, right – CO) for the standard flame under stoichiometric conditions (ϕ = 1.0), measured with the FTIR hyperspectral imaging apparatus.

In EMPRESS2, the flame will be used to facilitate the development of two new practical flame thermometers. The first, a low-cost (i.e. thousands of euros rather than tens of thousands) multi-spectral imaging system for flames, will be developed and calibrated against the standard flame, then demonstrated in industrial applications e.g. fire resistance testing and natural gas production. The second device is an infrared on-sight/sweeping IR emission measurement system that can measure the 2D temperature profiles in flames or hot flue gases. This will then be calibrated against the standard flame, and demonstrated in a $NO_x$ selective non-catalytic reduction process. There are three key tasks:

### *3.3.1. Task 3.1 Supply and coordinate circulation, and the calibration of a portable standard flame*
The aim of this task is to supply the partners (DTU and UC3M) with NPL's (portable) flame reference standard for use in their facilities. Before and after each journey away from NPL the flame is checked and re-calibrated using the Rayleigh scattering thermometry system [27] to ensure consistent performance.

**Progress:** The flame flowmeters and reference platinum resistance thermometer (PRT) have been re-calibrated successfully. No evidence of drift outside the uncertainty of calibration was found. The standard flame system, as a whole, has also been re-calibrated with the NPL Rayleigh scattering thermometry system for propane/air equivalence ratios of 0.8 to 1.4, in steps of 0.1. The measured temperatures were all within the standard uncertainty of 0.5 %.

### *3.3.2. Task 3.2 Development of a thermal imaging system*
The aim of this task is to develop a multispectral thermal imaging system that is suitable for temperature measurements in various industrial applications with overall uncertainties better than 0.5 %. The system will use a multi-filter based concept incorporated with an IR imaging camera.

DTU and UC3M will take a low spectral resolution (i.e. wavenumber resolution of 1 $cm^{-1}$) approach for temperature measurements. High resolution experimental IR emission spectra obtained on the portable standard flame will be used to simulate of low-resolution (band-) spectra, in order to investigate the influence of spectral resolution on the accuracy of the temperature calculated from the

IR emission spectra. Additionally, the optimal centre wavelengths and spectral bandwidths for use in the temperature measurement of flames will be defined.

**Progress:** The low spectral resolution approach for temperature measurements has been tested. Interferograms obtained on the NPL standard flame in the EMPRESS project [16] have been cropped around the zero path difference point in order to simulate low resolution spectra and to retrieve temperature values from them. On a central point about 20 mm above the burner, the measurement accuracy is quite good for resolutions of 1 $cm^{-1}$ and 2 $cm^{-1}$ (around 1 %). Theoretical emission spectra have been generated at high spectral resolution (0.5 $cm^{-1}$) for a variety of temperatures (T) and $CO_2$ column densities (Q) in the medium infrared region. Spectra have been integrated over bands of different spectral widths to simulate measurements from a multispectral system.

Quadratic functions have been used to fit T and Q as a function of the integrated radiances, and accuracy has been assessed for different numbers of bands and centre wavelengths. Fitting has been performed using principal components as independent variables, because they provide the optimal use of information and make it possible to compare also results based on high resolution spectra. It has been found that centre wavelengths are not critical as long as they cover the emission band of $CO_2$, and that the most influential factor in the accuracy of temperature recovery is the range of temperatures used to train the fitting function. For six bands in the region from 4 μm to 5 μm, the root mean square value for T is less than 1 K if the training range is between 1500 K and 2000 K. However, if it extends from 500 to 2300 K, root mean square values are larger than 30 K.

CEM will calibrate at least two of UC3M's IR cameras at CEM using a range of at least two different blackbodies up to 3300 K to provide traceability for UC3M's measurements in industrial applications.

UC3M, CEM and Sensia will develop a filter-based multispectral imaging system. A set of at least three optical filters will be tested in combination with a selected IR camera, and the best filters will be chosen for mounting on the filter wheel of the IR camera. The system will be calibrated at the facilities of CEM. UC3M will define a set of filters and will choose an IR camera best suited for operation with these filters, and will mount the filters on a rotating filter wheel that will be adapted to the camera. Calibration of the multispectral imaging system will be performed at CEM.

The performance of the multispectral imaging system developed above will be tested on two well-characterised flame sources (i.e. the portable standard flame and a Bunsen burner).

### *3.3.3. Task 3.3 Development of a sweeping emission measurement system*

The aim of this task is to develop a FTIR-based system prototype for on-sight sweeping IR emission measurements. An optimal temperature profile retrieval algorithm will be selected from low/high-resolution FTIR emission spectra using e.g. line-by-line models or the selected bands approach. The system performance and temperature retrieval algorithm will be investigated using the portable standard flame, targeting an overall uncertainty of 0.5 %. The sweeping system will be used for measurements of 2D temperature profiles in the first pass (900 °C to 1100 °C) of a waste incinerator. The results will be used for NOx selective non-catalytic reduction (SNRC) process optimisation and for the validation of CFD modelling by the end-user, B&W Vølund.

DTU and UC3M will select an optimal temperature profile retrieval algorithm from the high/low resolution IR emission measurements developed above. DTU will develop an FTIR on-sight sweeping/emission measurement system prototype for 2D profiles using the portable standard flame as a reference. DTU will test and calibrate the FTIR system against the portable standard flame. DTU will perform in-situ, on-sight, 2D temperature profile measurements for the optimisation of NOx SNCR processes at B&W Vølund, and for the validation of the CFD modelling (of B&W Vølund) of a waste incinerator.

**Progress:** Different algorithms for temperature profile retrievals have been considered. The most promising one (with respect to computational efficiency, time and accuracy) is based on a machine learning approach, where the training is done on the basis of a set of pre-calculated $CO_2$/$H_2O$ high/low resolution emission spectra at various temperatures and concentrations. This is being done in collaboration with the University of California (Merced, USA).

Various hardware implementations (FTIR and IR grating spectrometer with fast IR camera) have been considered. DTU and B&W Vølund are current planning first in-situ measurements at a waste incinerator plant in Sweden, who have particular interest in the sweeping system. B&W Vølund will design and implement the access ports for the measurements. The results of the measurements will be used in further FTIR sweeping system and data analysis development.

### *3.4. WP4: Traceable fibre-optic thermometry*

Completely new to EMPRESS2, a suite of new fibre-optic techniques will be developed with the aim of making traceable temperature measurements in harsh environments possible. Phosphor-based fibre-optic thermometry will be developed using a traceably calibrated phosphor to more than 600 °C using a new type of coating for the fibre. For ionising radiation environments, a hollow-core fibre-optic thermometer will be developed, which is suitable for high gamma radiation environments, as the hollow geometry renders the fibre potentially immune to the darkening effects. A distributed fibre-optic temperature sensor will be developed, alongside a traceable calibration method. Its performance will be investigated with a range of coatings. For high temperatures, a hybrid thermometer based on a Fibre-Bragg Grating (FBG) at the tip of the sapphire fibre and a blackbody will be developed which exploits the redundancy of the two complementary measurements, and which can be traceably calibrated. There are four key tasks:

#### *3.4.1. Task 4.1 Development of traceable phosphor-based contact thermometers to 650 °C*

The aim of this task is to develop, calibrate and test novel phosphor tipped fibre-optic thermometers up to 650 °C that are immune to electromagnetic interference. This will include field trials in suitably harsh environments to demonstrate their performance. NPL and DTI will each develop a phosphor-based fibre-optic thermometer to 650 °C and cross-validate. They will then jointly establish traceable calibration methods for the new fibre optic thermometers using fixed points and liquid baths from room temperature to 650 °C. The thermometers will then be trialled in a plasma storm of charged particles at DTI and a large magnetic field e.g. 1 Tesla (at a collaborator's site e.g. Danfysik A/S).

**Progress:** NPL have selected a phosphor ($Mg_4FGeO_6$:Mn) and binder (Ceramabind 643-1) and suitable high temperature gold coated fibres have been identified. Tests made of a prototype phosphor tipped fibre have confirmed that this phosphor will work well up to band above 650 °C when used in intensity ratio mode. An emission spectral response facility has been built to identify optimal wavelengths to use for the ratio measurements. A test fibre 'pig-tail' has been made and development of a dedicated ratio sensor system is underway (Figure 8).

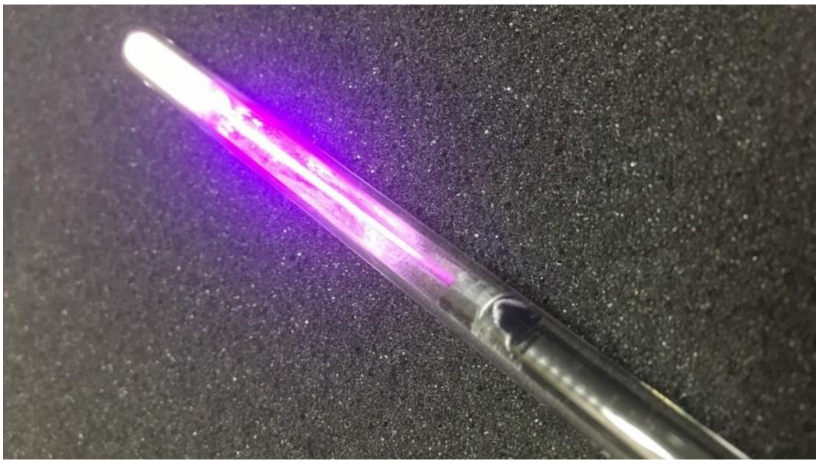

**Figure 8.** Fibre-optic ‘pig-tail’ phosphor thermometer. Excitation (blue light) yields phosphor emission (red light), giving a purple appearance.

DTI has additionally suggested the use of a solvent based binder which is easier to apply with an airbrush. A key advantage is that this does not react with aluminium, as is the case for some other water-based binders. The phosphor will be the same ($Mg_4FGeO_6$:Mn) and DTI will use the decay method with upgraded signal processing that matches the short lifetime at higher temperatures. A conceptual design of the probe has been developed, and a phosphor coating method has been developed to better control the reproducibility of the coating thickness and its quality.

*3.4.2. Task 4.2 Development of novel fibre-based thermometers for harsh environments*

The aim of this task is to develop and test two novel fibre-optic based thermometers. The first, incorporating hollow core fibres will operate over a modest temperature range (20 °C to 150 °C) but it will have the potential for immunity to high gamma fluxes. The second, comprising a flexible, ordered fibre bundle, will provide a thermal imaging capability for the remote inspection of hard to reach hostile environments. Both instruments will be tested in harsh environments.

**Progress:** UoS has investigated various types of hollow-core optical fibres (which offer higher immunity to gamma fluxes) for a phosphor-tipped fibre-optic thermometer, and have concluded that for phosphor excitation at 420 nm and emission at 660 nm, antiresonant-type fibres are the most promising options. The new design is able to deliver the excitation signal to the phosphor at the distal end and collect and guide the emitted signal back to the proximal end for analysis. Two types of anti-resonant hollow-core fibre samples, the ‘tubular’ and ‘nested antiresonant’ fibre have been fabricated and a significant effort deployed to interface them with standard optical components.

NPL has assessed these fibres for gamma radiation immunity in NPL’s irradiation facility. The transmission losses at 420 nm and 630 nm were approximately 16 dB/m and 12.3 dB/m respectively. The change in transmission following an exposure of 400 Gy was less than 2 %. The change in transmission ratio of two 20 nm bands at 630 nm and 661 nm (potential device specification) was less than 1 %. This demonstrates that it should be possible to operate an intensity ratio phosphor thermometer with high gamma immunity using hollow-core fibres.

UoS will also develop a thermal imaging fibre bundle, based on mid-IR transmitting glasses, for the remote inspection of hard to reach hostile environments. This will target an overall imaging resolution of more than 5000 pixels on a surface area of 5 $mm^2$, imaging distances of up to 3 m and two temperature detection ranges: 20 °C to 500 °C, and 400 °C to 1000 °C (the maximum operating temperature of the bundle will be 200 °C, so it will be displaced from the target). Testing and calibration will be performed at NPL, and trials in the field will be performed in forging/forming processes at AFRC.

*3.4.3. Task 4.3 Development of distributed temperature sensors using Brillouin scattering up to 650 °C*

The aim of this task is to develop a fibre-optic distributed temperature sensor (DTS) using Brillouin scattering for use in harsh environments, namely stainless steel manufacturing up to 650 °C, and to evaluate its performance.

CSIC and CEM will assess the facilities of ACERINOX in El Campo de Gibraltar and will decide on the most suitable locations to test the fibre-optic DTS. CSIC, in collaboration with CEM, will design at least one fibre-optic DTS, with variants having different coatings of aluminium, copper and gold to suit specific applications. These will be optically characterised to assess the Brillouin frequency shifts, ageing, and attenuation of at least two different single-mode optical fibres. The response of the three different fibre-optic coatings to a range of different temperatures up to 650 °C will also be assessed. CEM, in collaboration with CSIC, will perform the calibration of at least three of the differently coated fibre-optic DTS up to 650 °C. Finally, ACERINOX will deploy the fibre-optic DTS to compare their measurements with those sensors used in their routine measurements.

*3.4.4. Task 4.4 Deployment of hybrid fibre-optic based high temperature sensors to 1500 °C*

The aim of this task is to develop novel fibre-optic based temperature sensors that will be capable of operation up to 1500 °C and to demonstrate that, with field trials in three extreme industrial environments. Specifically, Fibre-Bragg Grating (FBG) thermometers offer great potential for high temperature applications. However, silica-based fibres are currently limited to around 1000 °C and they are prone to grating degradation at higher temperatures. This task will develop Bragg and blackbody cavity fibre-optic sensors based on sapphire fibres with the aim of combining them in a single hybrid sensor. By doing this, confidence in the measurement will be greatly improved as the measurement uncertainty is expected to be halved.

IPHT will develop optoelectronics and signal processing instrumentation and prepare sapphire FBGs in test fibres. PTB will develop signal processing algorithms for the temperature dependence of the asymmetric resonance peak of the FBGs in relation to the stability, repeatability and resolution of the measurements. JV will advise on the compatibility of the sapphire FBG with the blackbody part of the sensor. The output will be a functioning sapphire FBG with associated read-out instrumentation.

**Progress:** So far, IPHT and PTB have established a design for the sapphire FBG thermometer. PTB has designed, purchased and assembled a measurement setup for the high resolution spectral analysis of FBGs, which is based on a tuneable laser source, and IPHT have developed inscribed Fibre Bragg gratings with an operating wavelength of about 1540 nm in several fibres with a length of more than 80 cm, to enable the insertion of the probe into the calibration furnaces at PTB. The next step will be the packaging of the sapphire fibres, protection tubes, and conventional optical fibres.

An FBG thermometer will then be traceably calibrated up to 1500 °C at PTB. IPHT and PTB will assess the stability and reproducibility, as well as effects such as laser power self-heating, heat conduction, and thermal gradients.

JV, IPHT and PTB will analyse mitigation strategies for fibre self-radiation, and investigate the feasibility of using multiple fibres or multiple spectral bands. They will also develop a metallic or ceramic cavity to create a blackbody for the sapphire optical fibre tip, and will measure the Planck radiation, mitigating against fibre self-radiation. JV will select suitable blackbody materials with respect to chemical tolerance to sapphire. IPHT and JV will develop calibration techniques. IPHT have performed initial experiments to investigate the temperature dependence of blackbody radiation collected by sapphire fibres, and the first tests using a niobium cavity have been performed. Other cavity materials are also being investigated, and the assessment of fibre self-radiation is ongoing.

*The hybrid thermometer*

These two techniques will then be merged to create a hybrid thermometer. IPHT will adapt signal/data processing techniques to improve robustness against spurious effects e.g. thermal expansion, and will fabricate a sapphire hybrid thermometer packaged for laboratory calibration. JV, PTB and IPHT will investigate the effect of strain and thermal expansion on the measured signal, and will adapt signal processing with respect to fibre self-radiation and sensor position.

Following the manufacture, testing and validation will be performed to identify robust ways to merge the data from the two sources. Thermal cycling between room temperature and 1500 °C will be performed to assess the stability, and a validation with ITS-90 fixed points will be carried out over this temperature range. The hybrid sensor will be demonstrated in harsh industrial environments in the NPL gamma-ray facility, in silicon processing at Elkem, and in industrial furnaces at MUT.

## 4. Conclusion

A new European project, EMPRESS2, has been described, and the progress in the first quarter (nine months) presented. The aim is to enhance the efficiency of high value manufacturing and industrial processes by improving temperature measurement and control capability. This project seeks to address four contemporary thermometry challenges in this sector, and new developments from this and its predecessor project, EMPRESS, have been described. The key developments are in the areas of phosphor thermometry for surface temperature measurement, characterisation and improvement of ultra-stable thermocouples, application of a portable standard flame for developing new commercial flame imaging and spectroscopy-based instrumentation, and a suite of new fibre optic thermometers. The theme running through all the activities is the establishment of in-process traceability to the ITS-90, and the demonstration of the new thermometry techniques in-process by application to contemporary process control challenges.

## Acknowledgments

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