Improving temperature sensing for new reactors

Substantial improvements in high temperature measurement have been made in the last few years at national measurement institutes, which can be of benefit to the nuclear industry. By Jonathan Pearce, Michael de Podesta, Claire Elliott and Graham Machin

Within the next decade, a new generation of nuclear power plants will progressively replace those currently in use. To improve the efficiency of these new power plants they are required to operate at higher temperatures than the current generation (that is, with outlet temperature up to and beyond 1000°C compared with 500°C–800°C at present, depending on the type of reactor). The current temperature sensing technology, largely based around mineral-insulated metal-sheathed Type K thermocouples, is inadequate for the new challenges posed by the higher temperature environments. To maintain the safety and long-term reliability of such plants it is therefore essential that new temperature measurement sensors and methods for in-situ measurement are investigated and developed.

To meet these challenges, a project entitled 'MetroFission' was launched in 2010 within the framework of the European Metrology Research Programme (EMRP) to improve a wide range of aspects of sensing in nuclear environments. Temperature measurement comprises one of the nine work packages of this project. The partners involved in temperature measurement are national measurement institutes (NMIs) from Spain (CEM), France (LNE), and the United Kingdom (NPL). The MetroFission project involves 12 European laboratories working on projects such as high-temperature thermodynamic models, radionuclide measurement techniques and calibrated fluence standards for high-energy neutrons.

Temperature measurements in the nuclear industry are usually performed in challenging conditions due to high temperatures and ionising radiation. The temperature sensors are therefore prone to drift (change over time), transmutation (the conversion of one chemical isotope into another through nuclear reactions) or even breakage. The best capabilities of measurements in this field, in the harsh environment of a nuclear plant, are at the level of several tens of degrees Celsius for temperatures around 1200°C–1500°C, a level at which the sensor may be required to operate. Various instruments were developed 30 – 40 years ago for use under severe conditions (neutron irradiation) but the stability and accuracy of those instruments was, and still is, insufficient.

The development of specific contact sensors based on materials having very low neutron absorption cross section (molybdenum and niobium), in-situ self-validation of thermocouple calibrations, or contact sensors based on a different measurement technique (acoustic thermometry) are among the possible solutions. These sensors are essentially unaffected by transmutations—they are more adapted to the harsh environments—and should, in principle, exhibit lower drifts. These specific sensors aim to address the needs for improved measurements on-site in terms of accuracy and reliability. Understanding the performance of these specific temperature sensors needs the support of NMIs particularly for the study of sensors' metrological characteristics and to develop traceability routes to internationally agreed standards.

Table 1: The defining fixed points of the International Temperature Scale of 1990 (ITS-90) above 0°C

Substance	State	Temperature t90/°C
H_2O	Triple point	0.01
Ga	Melting point	29.7646
In	Freezing point	156.5985
Sn	Freezing point	231.928
Zn	Freezing point	419.527
Al	Freezing point	660.323
Ag	Freezing point	961.78
Au	Freezing point	1064.18
Cu	Freezing point	1084.62

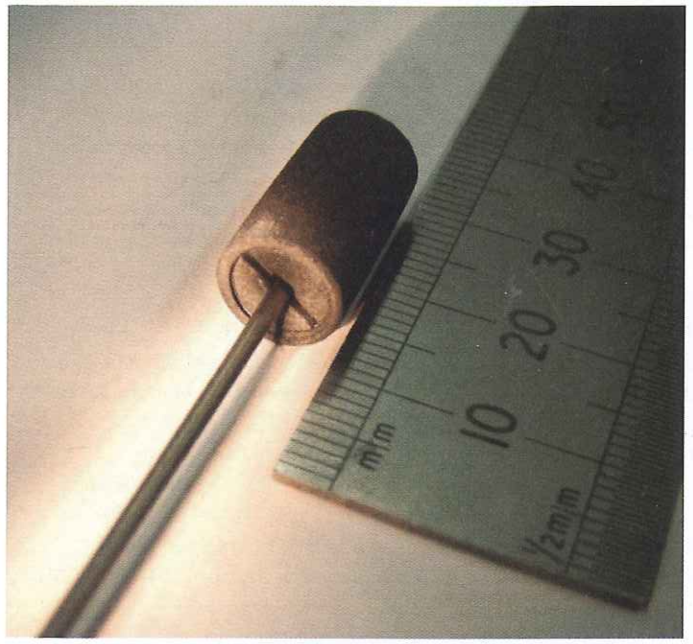
MetroFission aims

The aim is to develop several innovative methods to improve temperature measurement in the challenging environment posed by fission reactors. Four main areas will be investigated: (1) the traceability and assessment capability for new thermocouple types, (2) new temperature fixed points, (3) in-situ self-validating capability, and (4) highly innovative, permanently driftless, primary thermometry temperature sensors. The main tasks in these areas are summarised below.

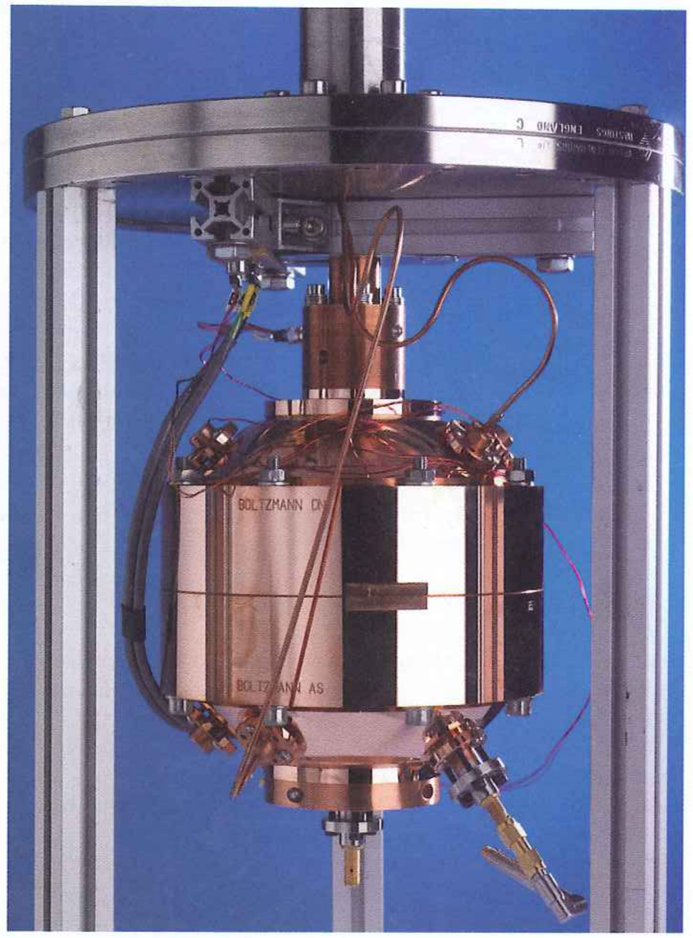
Industrial temperature measurements are mainly based on either base metal thermocouples (Type K and N) or noble metal thermocouples (such as Pt-Rh alloy-based Types R, S, and B). Conventional thermocouples (in particular Type K) have a maximum working temperature around 1100°C and undergo transmutations under ionizing radiation resulting in rapid decalibration. The Mo/Nb thermocouple family offer an interesting alternative, especially for the next generation of power plants: they exhibit a low neutron absorption cross section and can bear much higher temperatures (up to 1600°C) [1, 2]. The overall objective of this task is to investigate the metrological characteristics of these sensors and the means for enhancing their stability and ensuring their traceability. The main steps for achieving this task will be:

- identify the thermocouples to be constructed within the Mo/Nb family
- develop optimum construction capability for the chosen thermocouple(s)
- construct the thermocouple(s) and measure their reference function(s) (temperature–emf relationship)
- study the thermocouple(s) for improved stability (for example, define annealing procedures)
- assess thermoelectric homogeneity of thermocouples at the Ag fixed point and/or Cu fixed point and/or at lower temperature in liquid-stirred bath.

This should establish a reference function and optimum construction method for the selected Mo/Nb family thermocouple(s) to enable their use in nuclear and other industrial sectors.



Above: **Figure 1: A W-Re thermocouple with a miniature graphite crucible mounted on the measuring junction**



Right: **Figure 2: the NPL-Cranfield acoustic resonator**

In addition, thermocouples made from the pure elements Pt/Pd are reaching technical maturity, offering improved stability, repeatability and homogeneity up to 1500°C. The advent of high-temperature fixed points (HTFPs) has made the accurate calibration of Pt/Pd thermocouples possible, giving access to their superior performance. Recent design innovations by NPL have resulted in a robust version, which has been developed in conjunction with industrial partners. In the longer term it is envisaged that industrial use of Pt/Pd thermocouples will become widespread, with considerable benefits for process control.

New temperature fixed points

Pt/Rh thermocouples are employed in the majority of power and process applications, such as power generation plants, aerospace heat-treatment plants, and gas turbines up to about 1600°C. Until recently, the uncertainty of calibration at temperatures above 1100°C was restricted by the lack of HTFPs. However, a new generation of HTFPs has led to a step change improvement in high temperature measurement taking place across the world, with NPL playing a leading role [3].

The new HTFPs are based on ingots of metal-carbon eutectic (and peritectic) alloys, which have invariant melting temperatures above the Cu fixed-point temperature (1084°C). The use of metal-carbon alloys in graphite crucibles yields extremely repeatable temperature fixed points because the eutectic composition has the lowest temperature in the liquid phase. This property means that the temperature fixed point, when realised in a graphite crucible, automatically adjusts itself to the eutectic composition, hence maintaining its impressive repeatability. This property now enables the use of HTFPs for the calibration of thermocouples (and radiation thermometers) with unprecedented accuracy.

One objective is to perform post-irradiation drift studies using one or more fixed points from among the existing ITS-90 fixed points (Ag, Cu) and new points based on metal-carbon alloys (such as Fe-C 1153°C); see Table 1. The uncertainty level aimed for lies closer to +/-0.2°C than the +/-1.5°C level currently attainable with conventional methods [3].

The steps of this task are as follows:

- Identify the fixed point cell(s) to be constructed
- Construct the fixed point(s) cell(s) and perform robustness tests (risks of breakage)
- Assign temperature values to the cell(s)
- Transfer the capability to the user with clear guidance for usage

This part of the project has already made good progress, with a number of Fe/C fixed point cells being constructed by NPL and LNE and their performance assessed [4]. The outcome will be one (or more) Fe/C HTFP cells prepared for post-irradiation studies.

Thermocouple self-validation

The reliable use of noble metal thermocouples is limited to approximately 1600°C. If radiation thermometry is not feasible, the only solution for the measurement of higher temperatures is to use refractory metal W/Re thermocouples, but these are prone to substantial drift and damaging embrittlement. A possible new solution at these high temperatures is through in-situ 'self-validation' whereby one or more temperature fixed points are incorporated into the measuring junction of the thermocouple. Every time the melting temperature is passed, the thermocouple calibration can be re-validated as the sensor output shows an interruption while the fixed point material melts or freezes. A prototype of such a device is shown in Figure 1.

Therefore, a third objective in the project is to demonstrate the practicality of self-validation methods for thermocouples, utilising robust micro-crucibles made of graphite rather than the ceramic currently available in lower-temperature self-validating thermocouples [5]. The self-validation technology that we propose could even be adapted to higher temperatures (even above 1700°C) and could in principle be adapted to Generation IV reactors. This would be a highly-innovative step and should lead to significant improvements in high-temperature measurement. This work will focus on solving the thermal environment issues of the self-validation method. The aim is to study original self-validation techniques and sensors for future implementation in the irradiation environment. The following steps are required:

- Design self-validation methods for thermocouples in the temperature range of interest
- Construct (at least) two different designs of self-validating sensors for (at least) two temperatures
- Compare performance of the two different self-validating sensors in two different thermal environments at NPL and LNE
- Perform thermal exposure to demonstrate enhanced in-use performance

At the end of this task, in-situ validation methodology will be demonstrated, although use in a neutron irradiation environment will be the subject of a future study. Papers will be submitted for publication describing the sensors and the outcome of laboratory tests.

Acoustic thermometry

Thermocouples generate an electromotive force (EMF), which depends on temperature. However this EMF cannot be calculated from first principles, and so thermocouples must be calibrated against known temperatures. In addition, the resulting emf-temperature relationship of a particular thermocouple can change rapidly in service.

To avoid this problem, a sensor that measures thermodynamic temperature is needed, but these are not generally practical in typical measurement situations. NPL recently completed construction of a very precise primary thermometer. The device exploits a fundamental relationship between the speed of sound in a gas and the speed of motion of the gas molecules. The way in which sound is transmitted through a gas is complex, involving rapid compressions and expansions of the gas. Given this complexity, it is astonishing that speed of sound is directly related to the average molecular speed by a pleasingly simple expression. At low pressures, the speed of sound in a monatomic gas, c, is related to molecular speed by:

$$c = \sqrt{\frac{5}{9}}\, v_{RMS}$$

In this equation, v_{RMS} is the 'root mean square molecular velocity', that is the square root of the average of v^2. And since the average molecular speed is fundamentally linked to temperature, the low-pressure speed of sound is given by:

$$c^2 = \frac{\gamma RT}{M}$$

In this equation, gamma is the adiabatic index for the gas (5/3 for argon), R is the molar gas constant (8.31 J/(K*mol)) and M is the molar mass of the gas (39.95 x 10^{-3} kg/mol). The device allows us to determine temperatures by measuring the speed of sound. This technique is known as 'acoustic thermometry'.

This primary thermometer, at NPL, is used to measure temperature by determining the speed of sound in very pure argon gas flowing through a spherical resonator constructed by the ultra-precision manufacturing team at Cranfield University (Figure 2).

The outer cylinder shown is 148 mm in diameter and the spherical cavity within has a radius of 62 mm. NPL is developing a practical implementation of this technique using metallic tubes rather than spherical cavities.

In the course of this research, two simple ideas were combined to create a sensor that promises to both improve temperature measurement and reduce its cost. It was realised that timing pulses of sound travelling down a tube could also be used to measure the speed of sound. The tube could be straight, wound around an object, or embedded within it [6]. The material of the tube could be chosen for its cheapness or its robustness or, for example, to withstand radiation, without affecting the accuracy. With national and European funding, NPL is now constructing a demonstrator apparatus and is seeking partners to bring the benefits of this new concept to UK industry.

The method proposed is totally novel and could be used in a radiation environment to assess the drift performance of more conventional sensors, or used as a temperature sensing method in its own right. The lifetime of such a method would be envisaged to be as long as the useful operating life of the power plant—effectively fit-and-forget. The steps associated with delivering this task are:

- Design a practical primary acoustic thermometer for use to at least 1000°C, preferably to 1200°C
- Construct a primary acoustic thermometer, including development of suitable acoustic waveforms for signal identification in noisy environments
- Demonstrate use of the primary acoustic thermometer to identify the drift of temperature sensors by comparison with thermocouples through extended exposure in a high temperature environment (at NPL)

Papers will be submitted describing both the apparatus and the outcome of long-term high temperature tests. ■

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