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Ultrasonic High-Temperature Sensors: Past Experiments and Prospects for Future Use

**M. Laurie · D. Magallon · J. Rempe ·
C. Wilkins · J. Pierre · C. Marquié · S. Eymery ·
R. Morice**

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Abstract Ultrasonic thermometry sensors (UTS) have been intensively studied in the past to measure temperatures from 2080 K to 3380 K. This sensor, which uses the temperature dependence of the acoustic velocity in materials, was developed for experiments in extreme environments. Its major advantages, which are (a) capability of measuring a temperature profile from multiple sensors on a single probe and (b) measurement near the sensor material melting point, can be of great interest when dealing with on-line monitoring of high-temperature safety tests. Ultrasonic techniques were successfully applied in several severe accident related experiments. With new developments of alternative materials, this instrument may be used in a wide range of experimental areas where robustness and compactness are required. Long-term irradiation experiments of nuclear fuel to extremely high burn-ups could benefit from this previous experience. After an overview of UTS technology, this article summarizes experimental work performed to improve the reliability of these sensors. The various

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C. Wilkins is working as a consultant (retired from INL).

M. Laurie (✉) · D. Magallon
European Commission Joint Research Centre, Institute for Energy, Petten, The Netherlands
e-mail: mathias.laurie@ec.europa.eu

J. Rempe
Idaho National Laboratory, Idaho Falls, ID, USA

Present Address:
C. Wilkins
Idaho Falls, ID, USA

J. Pierre · C. Marquié · S. Eymery
Institut de Radioprotection et de Sûreté Nucléaire, Cadarache, France

R. Morice
Laboratoire National de métrologie et d’Essais, 1 rue Gaston Boissier, 75724 Paris, France

designs, advantages, and drawbacks are outlined and future prospects for long-term high-temperature irradiation experiments are discussed.

Keywords Fixed-point cells · Fuel testing · Harsh environment · High-temperature irradiation · Severe accident experiment · Ultrasonic Thermometer

1 Introduction

For temperature measurements up to 1280 K, Type K and N thermocouples perform quite well. However, their life expectancy and thermal drift at high temperatures present problems. Refractory metal thermocouples, containing W–Re, may withstand temperatures above 2280 K, but their decalibration rate due to transmutation in irradiation experiments is significant and difficult to correct. Recently developed Mo–Nb thermocouples appear promising, but their measurement range is more limited than W–Re thermocouples. At higher temperatures, approaching 3280 K, thin-wire ultrasonic thermometer sensors (UTS) offer robustness and longevity advantages over thermocouples.

Pulse-echo techniques with multi-zone thin-wire sensors at high temperature were chiefly used for nuclear fuel centerline temperature applications. With this technique, an axial temperature profile may be deduced by the use of multiple sensors in a single probe. The thin wire is usually enclosed in a suitable protective sheath that can withstand harsh environments. UTS may be used near the sensor material melting point.

The present article gives a general overview of the development and operating experience gained with UTS for in-pile centerline fuel temperature profiles and safety experiments in the scope of severe reactor accidents. Early in-pile applications as well as recent applications are described, and future prospects are discussed taking into account past difficulties in ultrasonic thermometry.

2 Ultrasonic Sensor Technology

2.1 Ultrasonic Thermometer Principle

A narrow ultrasonic pulse is generated in a magnetostrictive rod by a short duration magnetic field pulse produced by an excitation coil. The ultrasonic pulse propagates to the sensor wire, where a fraction of the pulse energy is reflected at each discontinuity (notches or diameter change). Each reflected pulse is received by the excitation coil, transformed into an electrical signal, amplified, and evaluated in a start/stop counter system. The time interval between two adjacent echoes is evaluated and compared to a calibration curve to give the average temperature in the corresponding sensor segment. When a number of notches are available on the wire sensor, the various measurements give access to a temperature profile along the probe. Figure 1 illustrates schematically an ultrasonic thermometer [1]. The sensor diameter typically ranged from 0.25 mm to 1.5 mm, and the length ranges from 10 mm to 800 mm (although there is no limit on the length that could be used). The velocity of longitudinal waves in a thin wave guide (less than one tenth of the wavelength) can be expressed as shown in the following

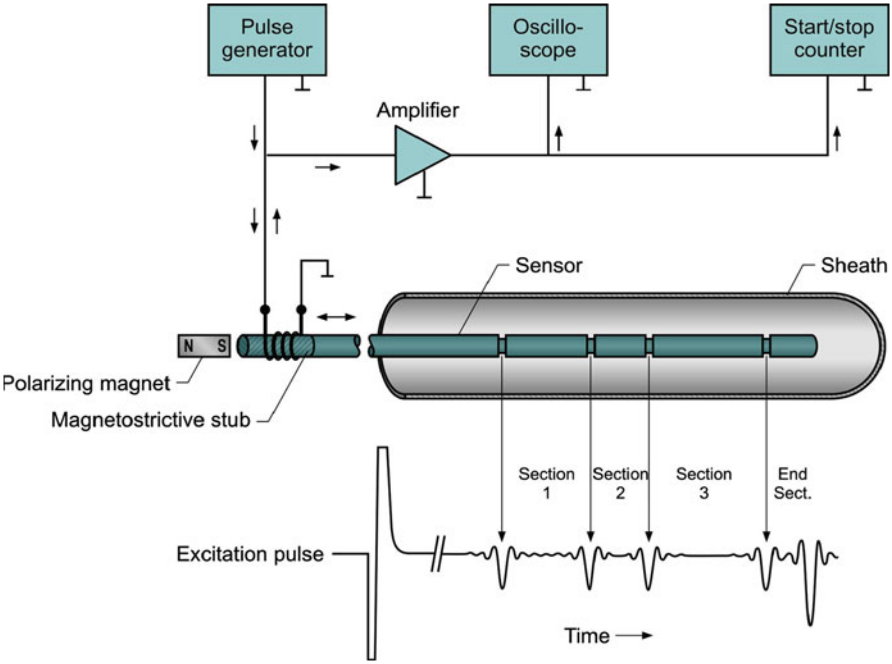

Fig. 1 Schematic view of an ultrasonic thin-wire thermometer

equation [2] where E is the Young's modulus of the sensor, ρ the density, and T the absolute temperature:

$$V(T) = (E(T)/\rho(T))^{0.5}. \tag{1}$$

Since the modulus and density are temperature dependent, the temperature can be deduced from the acoustic velocity. Nevertheless, the relationship is not so explicit. The temperature can only be estimated through calibration, using comparison techniques, reference temperatures being given by a calibrated optical pyrometer targeting the sensor wire. The sensitivity for tungsten is around $0.9\,\mathrm{ns \cdot K^{-1} \cdot cm^{-1}}$ above 1870 K.

Contact of the wire sensor with gas or liquid does not interfere with acoustic waves in the wave guide. On the other hand, solid contacts or deposits may produce discontinuities on the wire and cause spurious echoes that will prevent making the desired measurement. A protective sheath is then required to circumvent this problem. At the same time, spurious contacts between this protection tube and the wire sensor may lead to interfering echoes. This so-called "sticking effect," a significant issue encountered with ultrasonic thermometry, has mainly been encountered above 2080 K.

2.2 Manufacturing and Calibration Process

To avoid dispersive wave propagation in the rod, rod diameters are chosen to be less than one-tenth of the longitudinal wavelength. Discontinuities in the wire sensor should

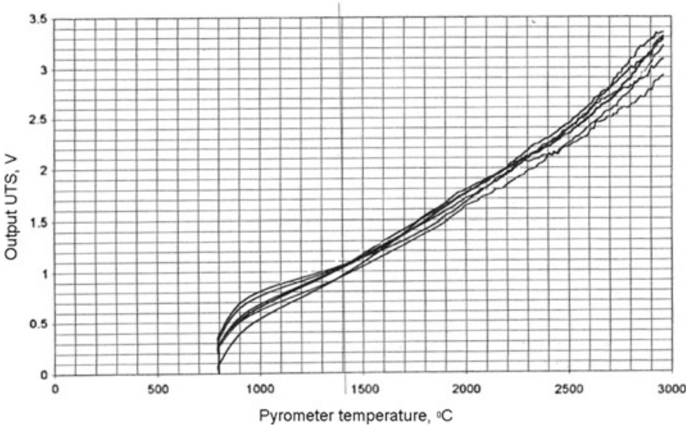

Fig. 2 Example of calibration curve for a multi-zone ultrasonic thin-wire thermometer

be placed at positions that minimize overlapping echoes. Several techniques have been developed for delinating UTS sensitivity. Tasman [1,3] used high quality machining to produce diameter changes. Arave [4] originally welded a smaller diameter sensor wire to the transmission line, but the most popular technique has been to engrave notches on the rod. The notches are of a depth that will produce reflections of comparable amplitude. For a 0.6 mm sensor rod, the notches often are limited to a depth of 0.1 mm [5] to alleviate problems with brittle sensor materials.

In one calibration method, the tungsten sensor is directly heated by an electric current; the wire sensor is used as an incandescent lamp in a tube. The first stage consists of stabilizing the crystalline structure by heating at a temperature close to 3280 K. After this heat treatment, thermal hysteresis phenomena diminish. The current is automatically varied in the desired temperature range. Reference temperatures were measured by a calibrated optical pyrometer. The calibration curve presented in Fig. 2 can be obtained by comparing output voltage with pyrometer readings.

The most common calibration method is to mount the sensor region in a high-temperature furnace. The process usually uses an inert gas environment. A preliminary heat-up/cool-down cycle stabilizes the grain structure in the sensor to minimize high-temperature drift. The sensor transit times are then measured as a function of temperature, using the zero-crossing point on a selected region of the echo pulses of interest. Figure 3 shows a representative calibration curve for thoriated tungsten. Reference temperatures are measured with a calibrated pyrometer. To minimize calibration error, it is essential to locate the UTS sensors region in a blackbody reference.

2.3 Probe Material and Instrumentation Performance

2.3.1 Probe Material

The choice of a sensor material is mainly driven by chemical compatibility with the sheath, reproducible calibration curves, and melting temperatures for the temperature

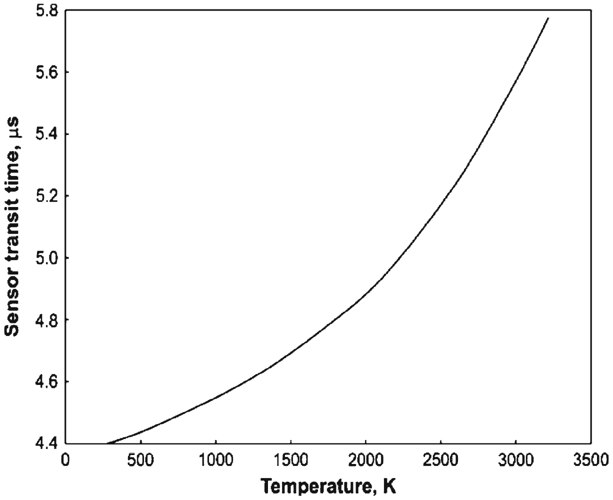

Fig. 3 Example of a representative calibration curve for thoriated tungsten

range of interest. It must also be compatible with environmental conditions, such as radiation. Characterization of acoustic properties has been done on a variety of sensor candidate metals, including stainless steel 302, nickel, titanium, zirconium, platinum, niobium, molybdenum, vanadium, rhodium, rhenium, tungsten, and thoriated tungsten [6]. Several metals showed unsuitable physical characteristics, non-reproducible calibration curves, or excessive attenuation.

Titanium could be used up to 1080 K. For temperature applications up to 1580 K, stainless steel and nickel–iron alloys appear to be good candidates with good sensitivity. Rhenium seems to be appropriate between 1780 K and 2880 K. Peak temperatures of 3030 K were achieved in laboratory testing. Due to the transmutation effect from rhenium to osmium, decalibration occurred. Above 2880 K, thoriated tungsten seems the only available material. Tasman [1,3] worked extensively with thoriated tungsten (up to 2 % thoria).

The main decalibration expected during in-core applications is due to transmutation of the sensor material. Structural changes, such as crystal dislocations caused by radiation, should be annealed out at the temperatures considered.

2.3.2 Instrumentation Performance

From a technical point of view, the calibration procedure contributes most to the final measurement error. With a directly heated sensor, several types of errors may occur, such as the use of one data point measured for the whole sensor length, pyrometer error, interference of deposited particles on the quartz tube, and the use of a polynomial fit. All the errors summed should lead to no more than a ±50 K overall error prior to considering the long-term drift process that may occur.

An absolute verification was performed with a calibrated melt wire wound around one of the zones of a calibrated UTS. The last measured value before the UTS echo was altered corresponded to a maximum deviation of 22 K [5].

To reduce uncertainties, several changes have been proposed, such as increased length between two notches to improve flight time measurement precision, averaging larger series of data, and enhancing electronic data acquisition systems.

3 In-Core Applications

As discussed in this section, the development of UTS included several Key in-pile tests. Ultimately, these tests demonstrate that these unique temperature sensors can withstand harsh environments for long durations.

3.1 HFR HRB Tests

The HRB capsules were irradiated in the high flux isotope reactor (HFIR) for periods from 2600 h to 6000 h. Rhenium pulse-echo UTS were used to measure centerline temperatures in high temperature gas reactor (HTGR) fuel [7]. After five reactor cycles at temperatures of 1180 K to 1380 K accumulating a thermal neutron fluence of $1.5 \times 10^{22}\ \text{n}\cdot\text{cm}^{-2}$ and a fast neutron fluence of $4.6 \times 10^{21}\ \text{n}\cdot\text{cm}^{-2}$, a post-test calibration was performed showing a drift of −1070 K at 1273 K. The very large decalibration is mainly related to the high capture cross section of rhenium (150 barns) used for long-term irradiation at high neutron flux. Calculations based on rhenium capture cross sections showed a 3 K drift at room temperature after an exposure to $10^{14}\ \text{neutrons}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$ for 100 h ($3.6 \times 10^{19}\ \text{n}\cdot\text{cm}^{-2}$) [8].

3.2 DC Tests at the Annular Core Research Reactor (ACRR)

Multiple temperature measurement zones were defined that allowed up to 14 measurement zones along the axis of a single thin wire to obtain a temperature profile. Tests DC-1 and DC-2 each had four UTS with five 10 mm long sensor zones. During UO_2 melting, all UTS embedded in DC-1 indicated a temperature near 3133 K (well in accordance with the expected value of 3123 K).

3.3 MP Tests at the Annular Core Pulse Reactor (ACPR)

Three molten fuel tests were conducted in the annular core pulse reactor (ACPR) using a UTS to measure melt temperatures and temperature gradients with a single instrument in a shallow molten UO_2 bed. Figure 4 shows a schematic of the test setup and instrument configuration. In these tests, the UTS were typically 0.5 mm in diameter and consisted of five ∼10 mm long sensors. The thoria sheath was 1.4 mm outside diameter and 0.7 mm inside diameter. Tests MP-1 and MP-2 yielded less satisfactory temperature data than expected due to binding between sheath and sensors. In the final in-core test, MP-3S, improved alignment ensured that a minimum of contact took place

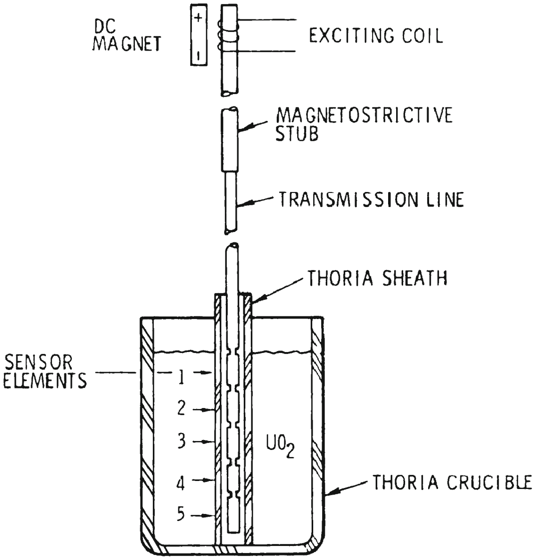

Fig. 4 Schematic view of an UTS measuring melt temperatures molten UO_2 bed

between the sensor and sheath. The UTS results were much more satisfactory than the preceding two tests.

3.4 RETSON Experiments at HFR

The RETSON experiment, which did not include fuel, demonstrated the stability of a thoriated-tungsten UTS in a reducing atmosphere under nuclear radiation [3]. In this test, the four-section thermometers were tested for 2000 h at 2273 K without any failure. The UTS were exposed to an integrated neutron dose of 1×10^{25} n·m^{-2} (thermal) and 1.5×10^{25} n·m^{-2} (fast). The maximum decalibration was estimated as less than ±30 K. By comparison, a W3Re/W25Re would be expected to decalibrate in the same time by at least 600 K.

3.5 PHEBUS FPT3 Experiment

Within this program dedicated to the study of fuel bundle degradation and fission product behavior under light water reactor severe accident conditions, two UTS with a rhenium sheath coated with iridium (outside diameter of 4 mm) inserted into a 1 mm zirconia protection tube were embedded in the test bundle [9] to measure a maximum temperature of 2480 K in a molten pool. Both UTS operated throughout the degradation phase of the fuel enclosed in the irradiation bundle with limited signal disturbances during the degradation phase (where transients in excess of 300 K·min^{-1} occurred).

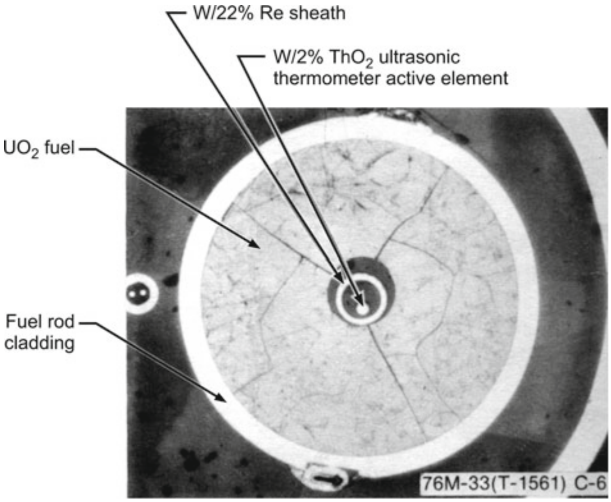

Fig. 5 Components in PCM PBF ultrasonic transducer inserted into PCM-2 fuel rod

3.6 PCM Tests at PBF

Ultrasonic thermometers with thoriated-tungsten transmission lines and sensors inserted into a protective tungsten–rhenium alloy sheath were used for fuel centerline temperature measurements in the power cooling mismatch (PCM) test series at the power burst facility (PBF). As the PCM tests were of short duration and extreme temperatures were not attained, the common failure modes experienced with UTS were not encountered in these tests. In that respect, operation was considered to be successful. Post irradiation examination [10] shows a cross section of the fuel rod containing the ultrasonic thermometer (Fig. 5). In these tests, the UT sheaths had a 1.6 mm outer diameter, and the probe consisted of one 50 mm long sensor.

3.7 CDC Tests at SPERT-IV

An experiment was designed to examine two UTS in pulsed core tests at the capsule driver core (CDC) facility of the SPERT-IV reactor. A 3.0 μs test and a 4.6 μs test were subsequently conducted to attain the highest possible peak temperature. Instrument responses from one of these tests are shown in Fig. 6. The peak temperature appears to be about 2080 K, and the probe response times were about 1 s to 2 s. Although both sensors (W5%Re/W26%Re thermocouple and UTS) had similar diameters, the less massive UTS, which lacks insulating material, appeared to have a faster response time.

3.8 WDC Test at ETR

An experiment designated as WDC-3-5 was inserted into the engineering test reactor (ETR). This test evaluated a prototype UTS design developed for fuel temperature

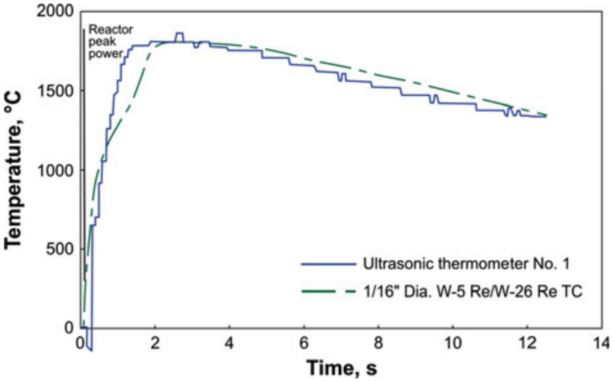

Fig. 6 UTS and thermocouple responses for one of the CDC tests

measurements up to 2680 K [4] in the experimental breeder reactor II (EBR-II). The UTS operated satisfactorily during several withdrawals and reinsertions, with the exception of periodic "sticking" between the sensor/transmission line and the protective sheath. Temperatures as high as 2980 K were registered during the two-week test.

4 Out-of-Pile Experiments

In FARO experiments constructed in Ispra for liquid metal fast breeder reactor severe accident studies, pure UO_2 was melted and delivered into a reaction chamber to study fuel impact and erosion against stainless-steel structures as much as fuel freezing phenomena [5]. During test L-09, the molten UO_2 remained stuck, and UTS were embedded. The probes operated at high temperature up to 3073 K for more than 1 h in oxide corium, although these sensors were designed for short-term use.

5 Limitations and Improvements

5.1 New Sensor Material and Anti-sticking System

For very high-temperature measurements, the already-developed thoriated tungsten seems unavoidable. At lower temperatures, stainless-steel sensors may serve for long-term use and should be evaluated in long-term irradiation campaigns. Unfortunately, among refractory metals with low thermal neutron cross sections, niobium has an unacceptably small temperature coefficient of acoustic velocity to be of practical use as UTS. However, preliminary review indicates that molybdenum is worth further investigation.

Several approaches were proposed in the past to solve the "sticking issue" including different types of spacer wires, thoria coating of the sensor, differential thermal expansion, welding standoffs to the sensor at strategic points, and rotating the sensor within its sheath. ThO_2 coatings gave an improvement up to 2580 K, but ThO_2 vapor

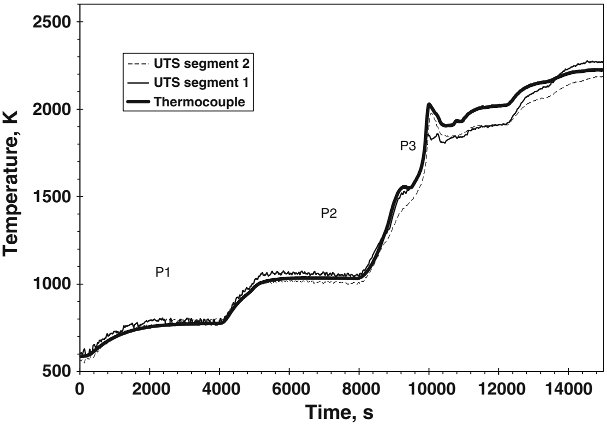

Fig. 7 Calibration of UTS segments with reference thermocouple for PHEBUS FPT3

enclosed in the inner space may condense on the wire sensor in cooler regions, leading to unwanted extraneous echoes. Wrapping a tungsten wire mesh on the sheath's interior appeared promising in the FPT3 experiment. However, no long-term solution has yet been shown to solve this sticking problem for all probe sizes and test configurations.

5.2 Electronics

For each reflected echo, a differentiator is used, and the time corresponding to the zero crossing is noted. The time interval between two echoes is determined through a start/stop integrator. The electronic system should have an uncertainty in the range of 5 ns to 20 ns to analyze time intervals in the microsecond range between two reflected echoes. The errors due to the electronics are small compared to other types of errors encountered during calibration. Signal processing should be enhanced to reduce signal disruption. Cross correlation techniques for signal recognition should be evaluated to determine if it is possible to detect and discard measurements when sticking problems occur.

5.3 On-line Drift System

During an FPT3 test, a thermocouple was attached to the UTS sheath between two notches for recalibration. As shown in Fig. 7, this thermocouple was taken as the reference during calibration plateaus P1, P2, and P3 for recalibration after transmutation of thoriated tungsten wire during the re-irradiation phase. An offset was chosen to correct the flight time between the two notches at the highest possible temperature. In order to mimic the molten wire of niobium previously used for absolute calibration, a re-usable sealed capsule containing a small amount of high-purity metal or binary alloy should be used. This fixed-point cell placed along the sensor in a lower temperature zone around one of the zones of the UTS could allow recalibration.

6 Conclusion

Although the UTS principle of operation is very simple, earlier investigations found that the signal processing was complex and that spurious echoes might occur. Nevertheless, for high-temperature monitoring when minimal instrument penetration is required, UTS with their ability to provide a temperature profile and to survive very aggressive environments remains one of the best if not the only possible option. As discussed in this article, one of the difficulties encountered with UTS has been overcome: the "sticking effect" seems to have been solved, as suggested in the FPT3 test (see Sect. 5.1). Recent advances with software should help resolve signal processing difficulties, such as overlapping echoes. Hence, it is recommended that UTS be re-examined for very demanding applications. In the nuclear field, UTS sensors should be developed because of their capability for in-core temperature profiling. As reported in this article, several options could be implemented to allow development of a reliable UTS sensor for long-term in-pile temperature detection.

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