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ABSTRACT

The Idaho National Laboratory (INL) recently initiated an effort to evaluate the viability of using ultrasonic thermometry technology as an improved in-pile sensor for detecting temperature during irradiation testing. Ultrasonic Thermometers (UTs) work on the principle that the speed at which sound travels through a material (acoustic velocity) is dependant on the temperature of the material. By introducing an acoustic pulse to the sensor and measuring the time delay of echoes, temperature may be derived. UTs offer several advantages over other temperature sensors. UTs can be made very small, as the sensor consists only of a small diameter rod which may or may not require a sheath. Measurements may be made near the melting point of the sensor material, as no electrical insulation is required; and shunting effects are avoided. Most attractive, however, is the ability to introduce acoustic discontinuities to the sensor, as this enables temperature measurements at several points along the sensor length (allowing temperature profiling with a single sensor). Although UTs have been successfully deployed in several applications, several problems have limited their success. This paper summarizes the capabilities of UTs, their prior applications, and the proposed project to develop an optimized UT probe. As described in this paper, options to resolve issues identified with prior UT use are under evaluation in this INL feasibility study. Once most promising options are demonstrated, an optimized prototype UT design will be developed and evaluated.

Key Words: In-Pile Instrumentation, Ultrasonic, Temperature Sensor, Temperature Profile

1 INTRODUCTION

Ultrasonic thermometry has the potential to improve upon temperature sensors currently used for in-pile fuel temperature measurements. Current methods for in-pile temperature detection primarily rely on either thermocouples or post-irradiation examination methods (such as melt wires). Commercially-available thermocouples (e.g., Type K, Type N, Type C, etc.) are widely used and cover a wide temperature range. However their use is limited. Type K and Type N thermocouples decalibrate at temperatures in excess of 1100 °C. Material transmutation causes decalibration in tungsten/rhenium (e.g., Type C) or platinum/rhodium (e.g., Type R or S) thermocouples in neutron radiation environments. Even though the High Temperature Irradiation Resistant Thermocouple (HTIR-TC) developed by Idaho

National Laboratory (INL) has overcome most of the difficulties associated with thermocouples [1], the resistivity of electrical insulators can degrade if subjected to high temperatures (in excess of 1800 °C), causing shunting errors. Thermocouples typically allow only measurement at a single location. Examination of melt wires and other post irradiation methods allow only the estimation of maximum test temperatures at the point of installation. The labor and time to remove, examine, and return irradiated samples for each measurement also makes this out-of-pile approach very expensive.

2 BACKGROUND

2.1 Principles of Operation

Ultrasonic Thermometers (UTs) work on the principle that the speed at which sound travels through a material (acoustic velocity) is dependant on the temperature of the material. The most studied (and, therefore, most well-developed) form of ultrasonic thermometry is the pulse echo method. By sending an ultrasonic pulse through a thin rod of known length, and measuring the time between the initial pulse and the reflection of the pulse from the opposite end of the rod, the average acoustic velocity (and, therefore, the average temperature of the rod) may be calculated. By introducing acoustic discontinuities, such as notches or sudden diameter changes, the rod may be segmented into a multipoint temperature sensor (the average temperature of each segment derived from timing of the successive reflections). In order to avoid wave dispersion effects, the rod should have a diameter of less than one tenth of the acoustic wavelength [2]. If this condition is met, the temperature -dependant acoustic velocity, $v(T)$, is related to density, $\rho(T)$, and elastic modulus, $E(T)$, (both properties are also temperature dependant) through the following equation:

$$v(T) = \sqrt{\frac{E(T)}{\rho(T)}} \quad (1)$$

A conceptual design of a typical multi-sensor UT system, with key components identified, is shown in Figure 1. As indicated in this figure, 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.

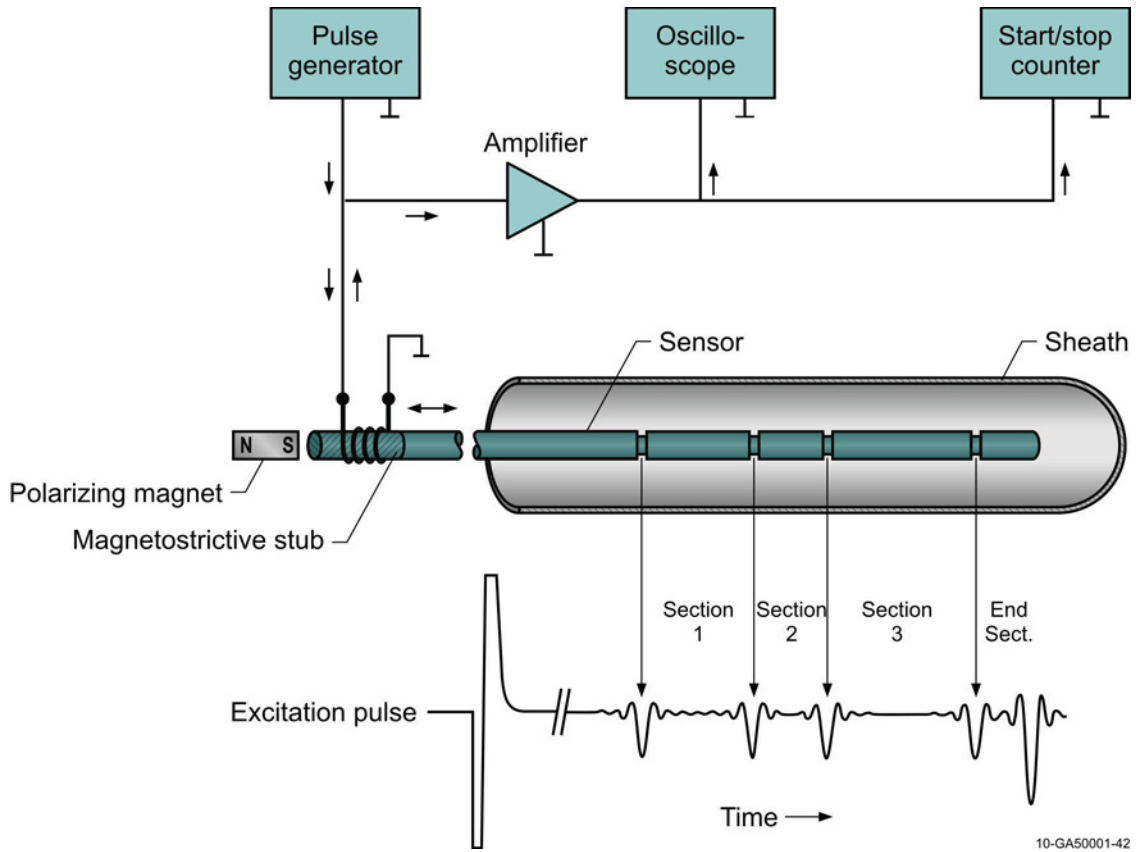


Figure 1. A typical multi-sensor pulse/echo ultrasonic thermometry system.

2.2 Prior Development

Prior UT applications have demonstrated the viability of this technology, but in-pile applications were primarily limited to high-temperature fuel damage tests, which ceased several decades ago. Selected applications of UT usage, which are identified in Ref 3, are summarized in Table 1.

Organization	Test	Maximum Temperature	Sensor Material	Comments
INL	WDC-3-5 Engineering Test Reactor	2707 °C	W-25%Re	Minor sticking between sensor and sheath
INL	Power Cooling Mismatch	2017 °C	Thoriated Tungsten	Short duration tests, no failures
INL	Capsule Driver Core	~1807 °C	W-25%Re	Demonstrated faster response time compared to thermocouples

Oak Ridge National Laboratory	High Flux Isotope Reactor-HRB	907-1107 °C	Rhenium	-1070 °C drift after test due to transmutation of rhenium
Sandia National Laboratory	Molten Fuel Pool	2860 °C	Thoriated Tungsten	5 sensor segments in molten UO ₂ , thoria sheath, temperature reached in 19 minutes
Nuclear Research and Consultancy Group	RETSON	2000 °C	Thoriated Tungsten	2000 hour test at 2000 °C results in less than 30 °C decalibration
Commissariat à l'énergie atomique/Ispra	FARO	2800 °C	Doped Tungsten	Operation for more than one hour in oxide corium
Commissariat à l'énergie atomique	PHEBUS FPT3	2207 °C	Thoriated Tungsten	Transients in excess of 300 °C/min experienced

3 ADVANTAGES OF ULTRASONIC THERMOMETERS

UTs have several advantages over other sensors [4]. UTs can be made with very small diameters while maintaining a high level of durability, as the sensor consists simply of a small diameter rod (typical diameters range from 0.25 mm to 1 mm, though a sheath may be required for some environments) [5]. In fact, a small diameter rod is desirable; as wave dispersion is avoided when the rod diameter is sufficiently smaller than the acoustic wavelength [2]. Temperature measurements may be made near the melting point of the transducer material. As no electrical insulation is required, shunting effects found in thermocouples and resistance temperature devices (RTDs) are eliminated. A clear line of sight is not required, as is the case for most optical pyrometry applications. Fiber optic cables are used in some pyrometry applications where line of sight is not possible, but darkening of the fibers has typically made this option unattractive for nuclear applications (though recent work performed in Europe [6] indicates that this technology may be viable). With proper selection of materials, UTs may be used in very harsh environments, such as high temperature steam or liquid metals. Perhaps the most appealing characteristic of ultrasonic thermometers is the ability to make temperature measurements at several axial positions using a single sensor, thereby measuring a temperature profile.

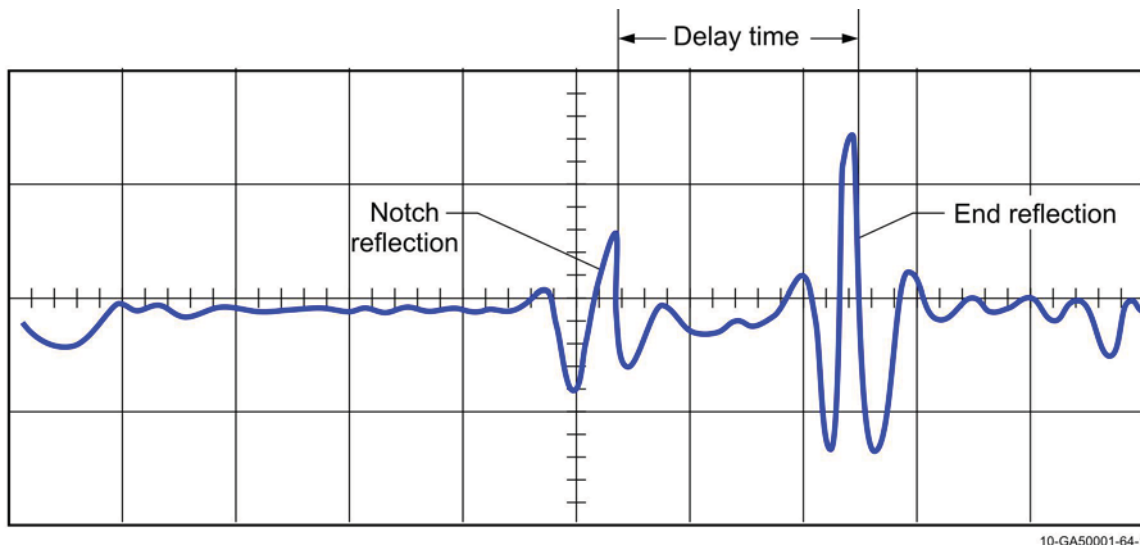
4 DESIGN ASPECTS TO BE ADDRESSED

The following section details some of the problems that have caused difficulties in previous efforts to develop an ultrasonic thermometer for in-pile applications.

4.1 Signal Processing

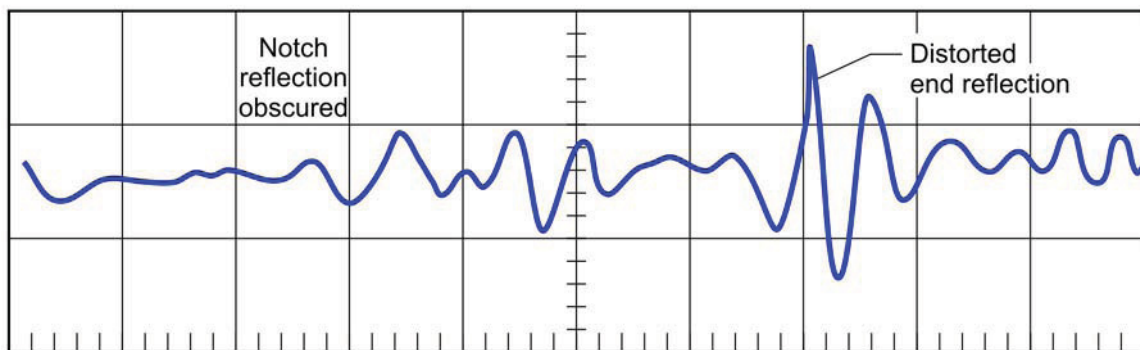
There are several problems that have caused difficulty in the development of UTs, particularly for high temperature measurements in nuclear environments. The primary difficulty in developing a useful ultrasonic thermometry system was in signal processing. The temperature of each sensor segment is derived by measuring the time gap between successive pulse echoes (reflected sound waves) [7]. Each

generated pulse results in multiple echoes (the number dependent on the number of sensor segments). These reflections may overlap. There may also be unwanted reflections, as shown in Figures 2 through 4 [8]. These reflections may be in the form of secondary reflections produced by echoes or reflections from points of contact between the sensor and its surroundings (the test environment or a protective sheath). It is essential to be able to identify, and accurately measure the time between, individual reflections. This can be simplified by generating a sufficiently short pulse, and by recording only one data set at a time (that is, generate a pulse and record all reflections before generating another pulse). Advances made in electronics since previous UT research was completed may allow for improvement of temperature resolution as well as automation of signal processing. Specifically, temperature resolution can be improved through faster sampling rates, as this allows for more accurate measurements of delay time.



10-GA50001-64-1

Figure 2. Normal single sensor echo waveforms showing notch and end reflections.



10-GA50001-64-2

Figure 3. Single sensor echo with signal interference caused by minor sticking.

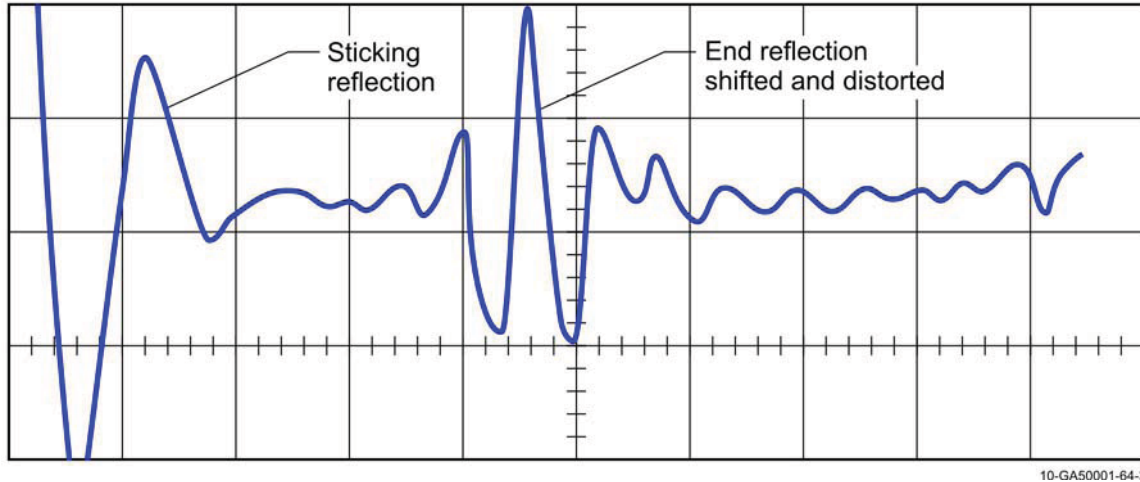


Figure 4. Single sensor with signal interference caused by severe sticking

4.2 Material Selection

Sensors used for in-pile temperature measurements are subjected to a very harsh environment. Therefore, proper material selection is crucial to the success of the sensor. Some conditions to be considered are high temperature (more than 1000 °C and potentially in excess of 2000 °C) melting and materials interactions. The latter includes interactions between sensor materials at high temperature as well as interactions between the sensor (or sheath) and the environment (which may include fuels, fill gases, coolants, and fission products).

A problem specifically related to high temperature measurements in nuclear research is transmutation of the sensor material. Materials previously found to be good candidates have come from the family of refractory metals. Particularly promising were rhenium, 2% thoriated tungsten, and tungsten doped with potassium, silicon, and aluminum (commonly used as a filament in incandescent light bulbs) [4,5,9]. Unfortunately, rhenium and tungsten will transmute significantly with increasing thermal neutron fluence, resulting in large sensor decalibration. Thoria, used in thoriated tungsten sensors, is added in order to control grain growth in tungsten. However, at high temperatures, the thoria has been observed to migrate from the sensor and vaporize. The thoria vapor then diffuses to cooler areas and precipitates. This can cause contact with the sheath, but also leads to excessive grain growth in the sensor (large grains can cause unwanted acoustic reflections) [7]. Refractory metals with lower absorption cross sections, as well as refractory based ceramics, may have the potential to minimize this problem.

A more fundamental consideration in selecting a material for use as an ultrasonic thermometer is the dependence of acoustic velocity on temperature [2,4,5,7-10]. This is an essential consideration as this dependence will have a large influence on the possible temperature resolution of the sensor. Figure 5 (re-created from Reference 9) shows the relative temperature dependence of the acoustic delay times (inverse of acoustic velocity) of candidate materials. From the figure, two candidates show temperature/velocity relationships that may be problematic. Niobium has a non-single valued response and a low overall sensitivity to temperature changes. Titanium has a very good response to nearly 940 °C. However, beyond this point, the temperature dependence appears to change, no longer being single valued.

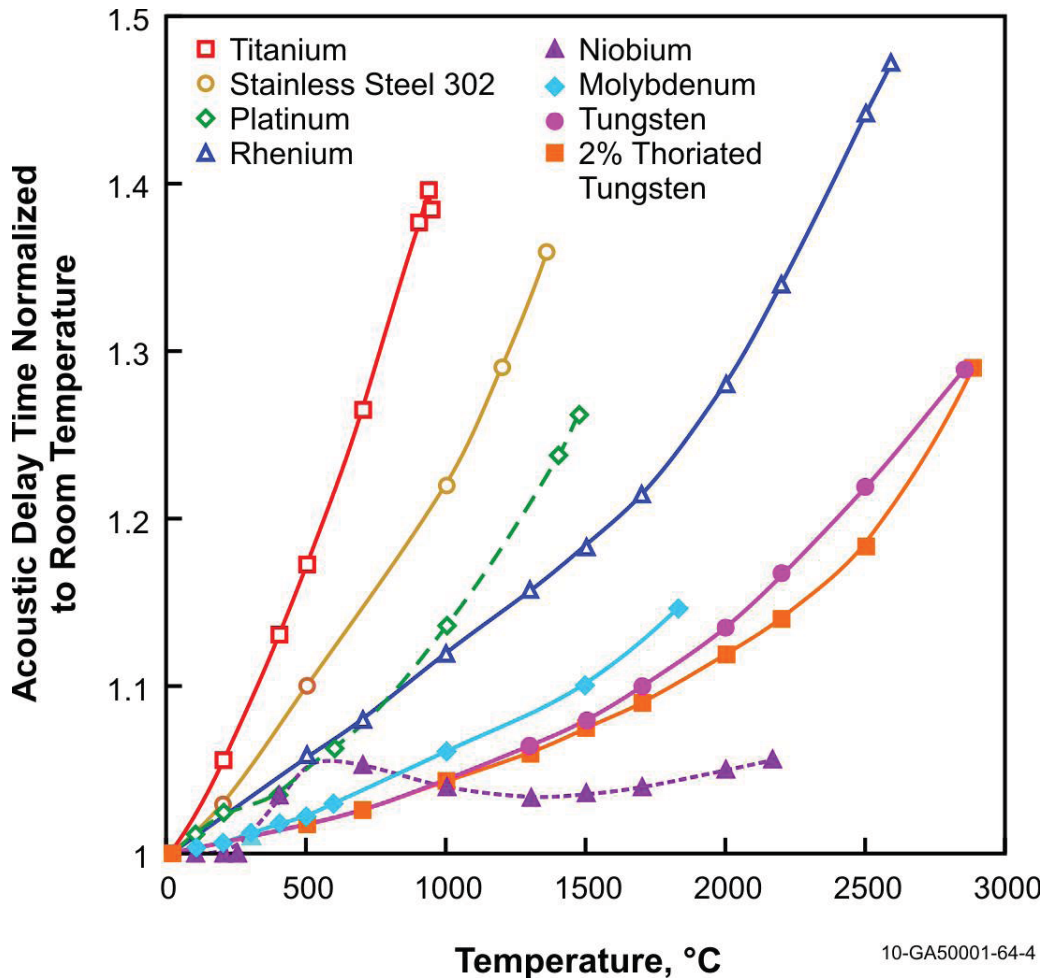


Figure 5. Relative acoustic delay times of several candidate materials.

4.3 Sticking

Contact welding of metallic sensors to protective sheaths (commonly referred to as sticking) can cause unwanted acoustic reflections [4,5,7], signal attenuation [4,7] and, in the case of severely embrittled sensors, damage to the sensor (embrittlement resulting from high temperature exposure). Previous attempts to preclude sticking have focused on minimizing contact between the sheath and sensor. This has been accomplished by the use of various forms of standoffs. These standoffs have typically taken the form of coils of tungsten wire wrapped around the sensor, or small protrusions of materials at points along the sensor length. These standoffs have not been completely successful, however, and may cause some unwanted reflections. In one case, a thoria sheath was used, which did appear to eliminate sticking to a large extent [4,5,7,10]. However, as noted above, at high temperatures, the thoria will evaporate, diffuse to cooler areas, and precipitate, causing sticking in the cooler regions. Newer materials and manufacturing techniques may yield new solutions to the sticking problem.

5 PROJECT DESCRIPTION

This project is organized into the following three tasks.

5.1 Task 1: Laboratory Evaluations to Optimize Test Setup

Prior to recommending an optimized design, bench-top testing will be performed at INL's High Temperature Testing Laboratory (HTTL) in order to demonstrate the viability of ultrasonic thermometers and optimize the testing setup. A preliminary design should include a transducer, a waveguide, a single segment sensor, and a signal conditioning/processing system. Each component will be investigated in an attempt to optimize performance. Primarily selection of proper materials and transducer types is critical.

Proper material selection is critical to the success of a new ultrasonic temperature sensor design. As refractory materials have been successful in previous designs for non-nuclear applications, these materials are initially being evaluated for new designs. Refractory metals with low neutron absorption cross sections have been successfully used in the INL-developed HTIR-TCs [11], and should be studied. Also, refractory based ceramic materials may have high temperature properties desirable in an ultrasonic temperature probe.

Ultrasonic temperature sensors typically consist of a magnetostrictive rod connected in a linear fashion to the sensor. This configuration results in a sensor device in which pulse generation and echo detection are accomplished with a single transducer. This system is simple and robust. Other technologies for generating/sensing of signals (i.e. piezoelectric materials) should be explored as improvements in pulse narrowing, amplitude sensitivity, and irradiation resistance may be achieved.

5.2 Task 2: Alternative Design Evaluations

This project is also focusing on developing an improved signal processing system to capture, record, and interpret signals from the sensor. Specifications for such a system are being identified, with development of the system performed in collaboration with a commercial vendor. The signal processing system will incorporate a pulse generator, and be capable of capturing and recording incoming echo signals with sufficient time and amplitude resolution to distinguish individual echoes. Options that will optimize the system's ability to separate overlapping pulses (such as cross-correlation and other modern signal analysis techniques) are being explored, as this will expedite the measurement process for multiple-sensor probes.

Though standoffs have not been entirely successful in resolving the sticking problem, the technique should be studied further as variations on the concept could prove more successful. Sheath materials and coatings should be closely examined, as reducing the high temperature diffusion potential between sensor and sheath could potentially eliminate sticking. The sticking problem may be avoided altogether if a sheath is not necessary. This is dependant on the conditions to which the probe is exposed. If the ultrasonic thermometer is constructed from a material that is compatible with the environment, or if a proper coating material can be applied, an unsheathed probe may be sufficiently robust. The selected probe or coating material must be non-reactive with any materials the probe may contact, must have a sufficiently high melting point, and must be highly resistant to corrosion in the test environment (this may include liquid water, steam, or liquid metals). For example, unsheathed UTs have been tested in liquids to study the attenuation effects of fluid viscosity [2]. A stainless steel sensor was tested in liquid sodium at 370 °C (this temperature was chosen to yield a high viscosity), while a tungsten sensor was tested in liquid water at room temperature (simulating the viscosity of liquid sodium at 1020 °C. Attenuation effects were found to be negligible.

Ultrasonic signals have typically been generated in the form of longitudinal waves, but it is possible to produce torsional waves as well. Previous work indicates that ultrasonic torsional wave velocity has a stronger dependence on temperature than longitudinal waves [4].

5.3 Task 3: Evaluation of Optimize Design

The temperature resolution of a UT system is strongly dependant on the sampling rate of the data acquisition system. A higher sampling rate allows for more accurate measurement of the delay time between pulse echoes and, therefore, the acoustic velocity. As the temperature is derived from the delay time (or the acoustic velocity), the ability to measure smaller changes in the delay time yields the ability to measure smaller changes in temperature. Current sampling technologies (for example, digitizing oscilloscopes) can provide sampling rates in the 1-5 gigahertz range, resulting in a time resolution of as small as 0.2 nanoseconds. For perspective, a previous study [2] estimated a temperature resolution of 0.1% at 2200 °C for a rhenium sensor with an effective length of 25 cm (the sensor was 5 cm in length, but multiple reflections were measured) and a sampling rate of 0.1 μ s. A sampling rate of 0.2 ns improves the time resolution of this system by a factor of 500. Theoretically, a similar improvement in temperature resolution is possible. This level of improvement is unlikely in practical applications, however, as other factors have a significant impact on the resolution. In the previously mentioned example, for instance, the estimate was made using a large effective length sensor at a temperature where the acoustic velocity of rhenium is very sensitive to temperature changes, both of these parameters increase resolution.

The accuracy of the UT is primarily influenced by the sensor's calibration. Temperature calibration is performed using secondary measurements. That is, the temperatures corresponding to delay time measurements are measured using a second sensor (i.e. a thermocouple or infrared pyrometer). Therefore, the overall accuracy of the UT is limited by the accuracy of the secondary sensor, as well as that of the delay time measurement. As mentioned previously, the delay time measurement technology has improved significantly. This leaves the calibration temperature measurement as the primary source of error. Accuracy of the secondary temperature sensors has improved over time; though not as much as delay time measurements. A further source of error in calibration is the positioning of sensors during calibration. For example, an optical pyrometer may be trained directly on an unsheathed UT; but if a sheathed UT is calibrated using a sheathed thermocouple, there are several layers of thermal separation between the sensors. The geometry used during calibration should be chosen carefully to maximize the accuracy of the UT.

Finally, once the most promising options are identified, one or more prototype multi-segment ultrasonic temperature probes will be produced and tested. A full test should include a long term installation in a high temperature test assembly installed in a high neutron flux environment, such as that found in the Idaho National Laboratory's Advanced Test Reactor.

6 CONCLUSIONS

The INL has recently initiated an effort to evaluate the viability of using ultrasonic thermometry technology as an improved in-pile sensor for detecting temperature during irradiation testing. As described in this paper, UTs offer several advantages over currently used temperature sensors. UTs can be made very small, as the sensor consists only of a small diameter rod which may or may not require a sheath. Measurements may be made near the melting point of the sensor material, as no electrical insulation is required; and shunting effects are avoided. Most attractive, however, is the ability to introduce acoustic discontinuities to the sensor, as this enables temperature measurements at several points along the sensor length (allowing temperature profiling with a single sensor). UTs have been used successfully for several applications; however, several problems have limited the success of these sensors. As part of the INL feasibility study, options to resolve issues identified with prior UT use are under evaluation. Once most promising options are demonstrated, an optimized prototype UT design will be developed and evaluated.

7 ACKNOWLEDGMENTS

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