Development of Ultrasonic Thermometer at INL

Joshua Daw – Idaho National Laboratory – joshua.daw@inl.gov

US DOE-NE programs are investigating new fuels and materials for advanced and existing reactors. A primary objective of these programs is to characterize the irradiation performance of fuels and materials. Examples of the key temperatures needed to evaluate fuel performance, as well as the desired accuracies and resolutions, are shown in Table I [1] . Similar measurement requirements exist for other parameters (i.e. fission-gas pressure). Ultrasonic technologies can be used to measure most of the key parameters of interest, but temperature was selected for initial development, as this is the most common measurement requested of irradiation programs.

	Estimated Peak Value	Desired Accuracy and Spacial Resolution
Fuel Temperature	**Ceramic Light Water Reactor (LWR): 1400°C**	**2%** **1-2 cm (axially)** **0.5 cm (radially)**
	Ceramic Sodium Fast Reactor (SFR): 2600°C	
	Metallic SFR: 1100°C	
	Tristructural-isotropic (TRISO) High Temperature Gas Reactor (HTGR): 1250°C	
Cladding Temperature	**Ceramic LWR: <400°C**	**1-2 cm (axially)**
	Ceramic SFR: 650°C	
	Metallic SFR: 650°C	

Table I. Summary of desired fuel measurement parameters for irradiation testing.

Project Description

Ultrasonic thermometry

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. Although larger-diameter, multipoint thermocouples are available, most thermocouples only measure temperature at a single location. Melt wires and other post-irradiation methods only allow estimation of maximum test temperatures at the point of installation. The labor and time to remove, examine, and return (if necessary) irradiated samples for each measurement also makes this out-of-pile approach very expensive. Prior ultrasonic thermometry 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 [2].

Theory of Operation

Waveguide based ultrasonic thermometers (UTs) work on the principle that the speed at which sound travels through a material (acoustic velocity) is dependent on the temperature of the material. The average acoustic velocity of a material can be measured 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. By introducing acoustic discontinuities such as notches or sudden diameter changes into the rod, the probe may be segmented into multiple zones (the average acoustic velocity of each segment derived from timing of the successive reflections). If the ultrasonic waves are non-dispersive (the rod having a diameter of less than one tenth of the signal wavelength

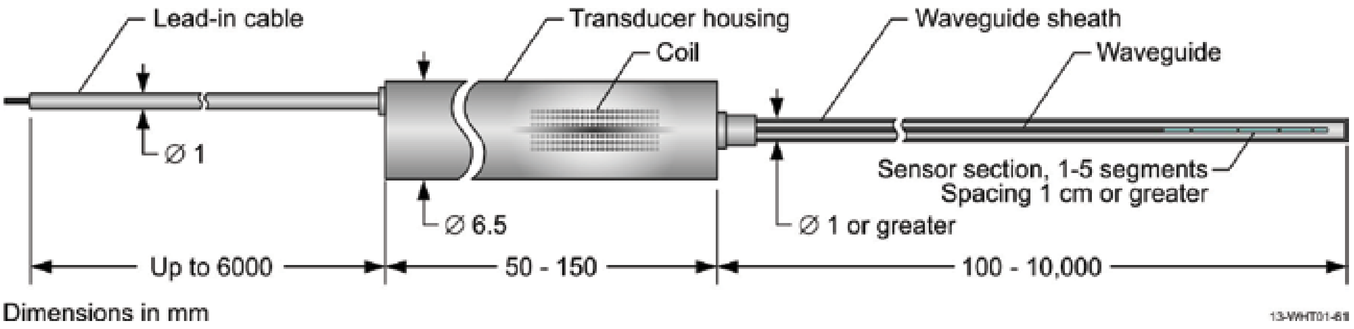

Figure 1. Schematic diagram of magnetostriction based ultrasonic thermometer.

[3]), the temperature-dependent acoustic velocity of the sensor material, $c(T)$, is related to the density, $\rho(T)$, and the elastic (Young's) modulus, $E(T)$, (both properties are also temperature dependent) of the sensor material through the following equation:

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

A typical multisensor 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 delay time measurements give access to a temperature profile along the probe.

Irradiation Testing

Until recently, INL-developed UTs had been tested at high temperatures in furnace environments (i.e., inert gas or vacuum atmosphere), but not in an irradiation environment. In-core qualification of a new sensor is a necessary step prior to deployment in irradiation test campaigns.

ULTRA

To generate and receive ultrasonic pulses and signals, two of the most commonly used technologies are piezoelectric and magnetostrictive transducers. Only the magnetostrictive transducers will be discussed here. The current capabilities of magnetostrictive transducers are typically limited

These technologies, which have performed successfully in out-of-pile tests, have not been well qualified in a test-reactor environment. The first in-core sensor, based on ultrasonic technologies and targeted for deployment, is the ultrasonic thermometer (UT), which can provide a temperature profile in candidate metallic and oxide fuels and would provide much-needed data for validating new fuel performance models.

to operation at frequencies up to the order of 100 kHz. However, mechanical coupling and guided-wave-mode generation makes magnetostrictive transduction ideal for low-frequency measurements, such as ultrasonic thermometry [4]. The irradiation behavior of magnetostrictive materials has not previously been studied in depth, leaving their appropriateness for use in irradiation tests unknown.

An NSUF-funded irradiation, dubbed the ULtrasonic TRAnsducer (ULTRA) irradiation test, led by Pennsylvania State University and executed at the Massachusetts Institute of Technology Research Reactor allowed for long-term irradiation testing of both piezoelectric and magnetostrictive transducers and evaluation of their survival within a high-radiation environment. The magnetostrictive transducer designed for this test was based on research by Lynnworth [5] and Daw [6]. The magnetostrictive transducers consist of a small driving/sensing coil, a biasing magnet, and a magnetostrictive waveguide. The ultrasonic signal is generated when a high frequency alternating-current pulse is driven through the coil. The induced magnetic field causes magnetic domains within the material to oscillate. The domains are pre-biased by the magnet to maximize the response. Received echoes are detected through the reciprocal effect.

The design of the transducers was identical to the UT shown in Figure 1, except the entire waveguide consisted of the magnetostrictive alloy being evaluated.

Candidate Materials

The magnetostrictive transducer materials were selected based on previous use in radiation environments, amounts of neutron sensitive materials, Curie temperature, and saturation magnetostriction.

Remendur

Remendur has the most history of use in nuclear applications of all magnetostrictive alloys, having been used previously for short-duration thermometry applications. Remendur

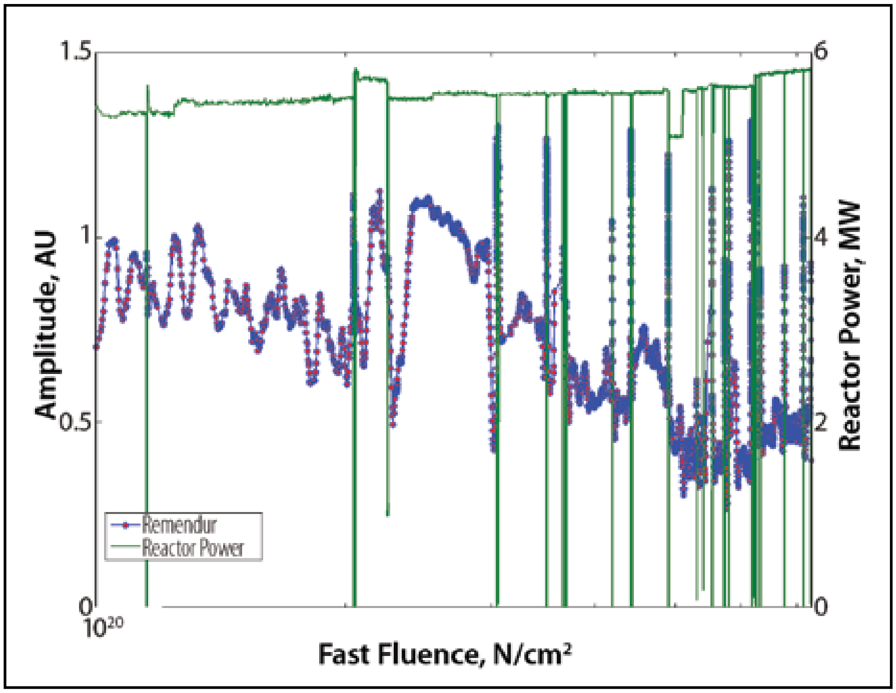

Figure 2. Remendur-element transducer-signal amplitude as a function of accumulated fast fluence.

has a high Curie temperature (950°C) and relatively high-saturation magnetostriction (~70 ρ strains). Remendur is an alloy composed of approximately 49% iron, 49% cobalt, and 2% vanadium. Because of its cobalt content, Remendur was not considered to be an ideal choice (due to concerns about the production of Cobalt-60 during irradiation). However, its successful prior use was deemed sufficient reason to warrant inclusion.

Figure 2 shows the normalized amplitude for the Remendur transducer as a function of accumulated fluence. There is a generally decreasing trend, but signal recovery after temperature transients indicates that some of the signal attenuation is due to temperature effects, in this case binding of the wire against the coil bobbin (see Figure 1 for transducer component diagram). As with the Galfenol transducer, increased noise after the first reactor restart post refueling may indicate an intermittent short in the drive/sense coil.

Galfenol

Galfenol is a relatively new alloy of iron and gallium (approximately 13% gallium). Galfenol is a member of the "giant" magnetostrictive alloys and has a very large saturation magnetostriction (100–400 ρ strains). It also has an appropriately high Curie temperature (700°C). Neither of its constituent elements reacts strongly with neutron radiation. These factors made Galfenol a very appealing magnetostrictive material candidate.

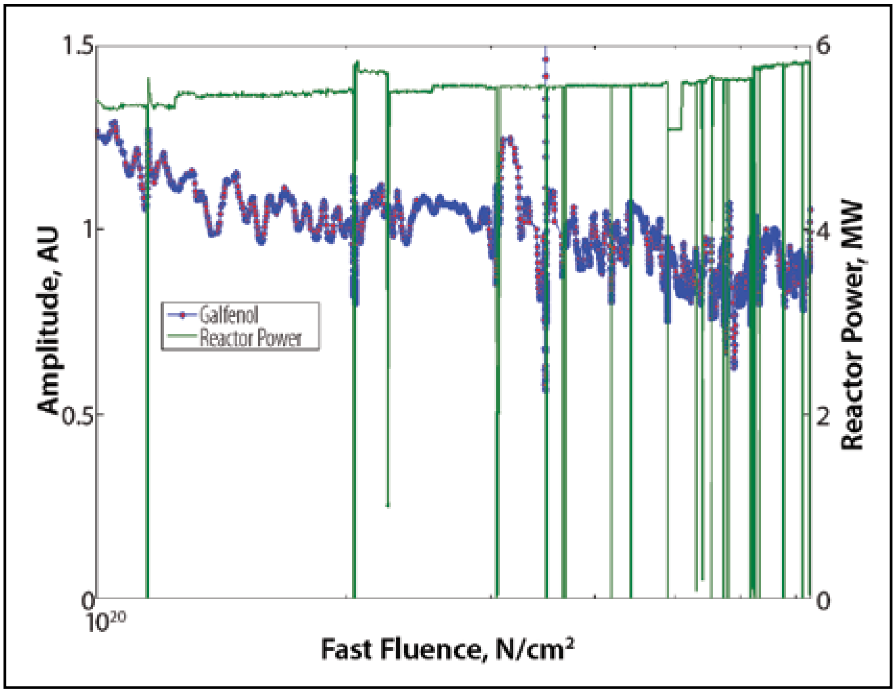

Figure 3. Galfenol element transducer signal amplitude as a function of accumulated fast fluence.

Performance of the magnetostrictive transducers was characterized using the normalized magnitude of the fast Fourier transform (FFT) of the first reflected acoustic signal (normalized to the time when the reactor first reached full power). The frequency-transformed signal is used because it is less sensitive to the interference effects of noise and signal transients

The Galfenol transducer was stable over the course of the irradiation, though the total peak-to-peak signal amplitude was typically on the order of one third that observed for Remendur. Figure 3 shows the normalized peak-to-peak amplitude for a Galfenol transducer as a function of accumulated fluence. The green trace shows the reactor power history. The Galfenol transducer shows steady operation during periods when the reactor power level was stable. There is little decrease in the signal strength over these periods. The decreases in signal strength observed when reactor power is increased appear to be due to increases in operating temperature, as the signal strength stabilizes shortly after each power increase.

The transducers were irradiated to a fast fluence of 8.8×10^{20} n/cm^2 (E>1 MeV). Post-irradiation examination of each irradiated material indicated negligible effects on the magnetostrictive behavior of either

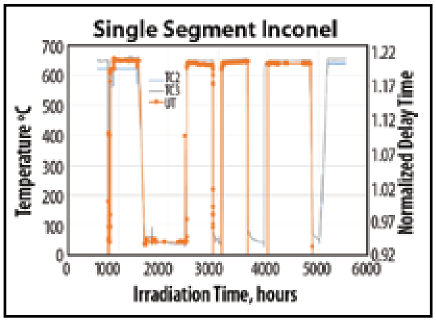

Figure 4. Single-segment Inconel sensor results

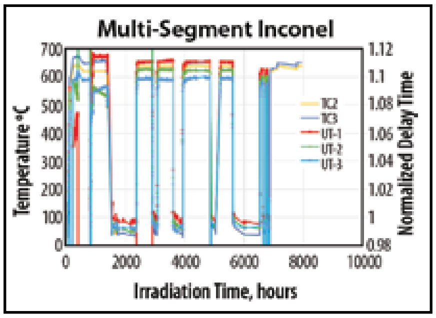

Figure 5. Multi-segment Inconel sensor results.

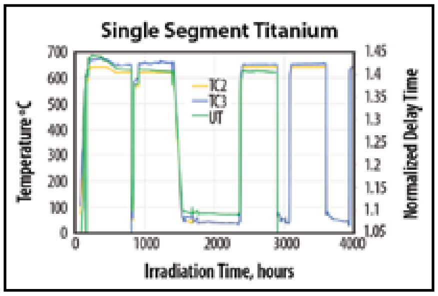

Figure 6. Single-segment titanium results.

tested material. Observed online signal changes were deemed to have been caused by thermal and mechanical effects within the transducers.

ULTRA2

Based on the results of the ULTRA irradiation test, a follow-on irradiation (ULTRA2) was selected for funding by NSUF. This test included INL-developed UTs and fiber-optic sensors provided by the French Atomic and Alternative Energy Commission (CEA) and by the University of Pittsburgh (only the UTs will be discussed here). Three UTs were included in the ULTRA2 irradiation test. Two of the experimental UTs use Inconel 606 wire as the sensing element; one had a single measurement zone, and the other had three zones. The third UT had a single zone and used commercially pure titanium wire as the sensing element. Spatial constraints of the MIT test capsule restricted the length of these UTs. As such, the UTs could not be directly calibrated without damaging the transducers. Performance was determined by examining the trends in measured delay times against temperatures measured by included thermocouples.

Each of the three UTs included in this test experienced failures of the driver coil before the completion of the test. This is likely due to a material change in a ceramic cement used to fill the transducer housing that was made between the original ULTRA experiment and ULTRA2. The new cement likely lost cohesion, allowing the coil wire to move during temperature transients and during refueling operations. All UTs survived for between ~5000 and 7000 hours and produced reasonable signals over that time.

Figure 4 shows the normalized delay time and thermocouple (TC) temperature of the single segment Inconel sensor. The data during initial reactor start-up were unusable, possibly due to a mechanical

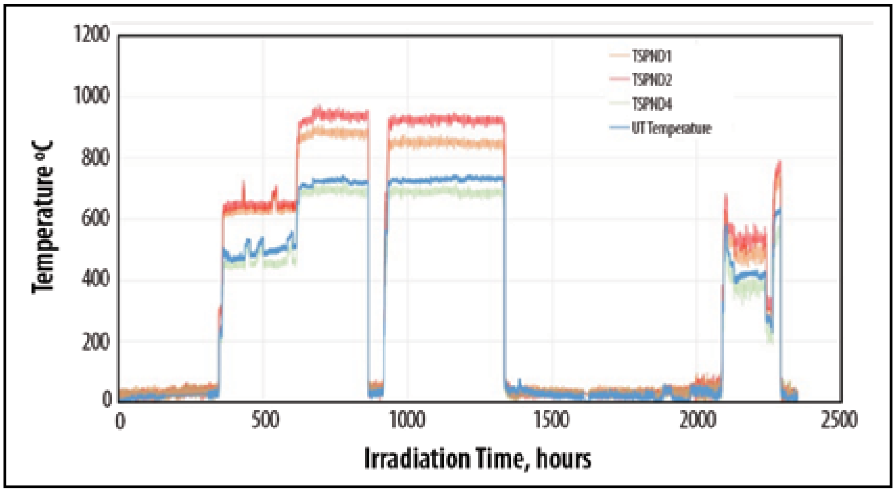

Figure 7 AGR 5/6/7 UT results

pinch in the sensor's wire that cleared up after temperature cycling. The signal follows the reactor temperature well, for most of the test. Some intermittent signal loss was observed over the last few reactor cycles. This is evidence that the coil was the component that failed, as any other component failing would not allow for a recovery.

Figure 5 shows the normalized delay time and TC temperature of the three-segment Inconel sensor. As with the single-segment sensor, for most of the irradiation, the signal closely matches the reactor temperature. Some anomalous behavior can be observed during the early part of the irradiation, seen as an opposing response between the first and second segments (as one signal increases, the other decreases proportionately). It is unclear at this point if this is a physical phenomenon or an artifact of the signal-acquisition process. This sensor also failed intermittently before finally failing after ~7000 hours.

Figure 6 shows the normalized delay time and TC temperature of the single-segment titanium sensor. This sensor performed well through almost 3000 hours before failure. Unlike the Inconel sensors, there was observed a slow decrease in measured delay time. The likely explanation of this drift is fast-neutron damage causing a slow increase in the elastic modulus of the titanium. The effect appears to have saturated by the last operational reactor cycle, but this behavior may make titanium a poor material for UTs.

AGR 5/6/7

Also based on the results of the ULTRA irradiation, one UT, using molybdenum as the sensing waveguide, was included in the Advanced Graphite Reactor (AGR)-5/6/7 irradiation test at INL's Advanced Test Reactor (ATR). This UT has performed very well through the early irradiation. This thermocouple was calibrated prior to installation in the experiment. Figure 7 shows the temperatures measured

Ultrasonic technologies offer the potential for high accuracy and resolution for in-pile measurement of a range of parameters, including geometry changes, temperature, crack initiation and growth, gas pressure and composition, and microstructural changes.

by the UT and by several thermocouples located near the UT. The thermocouple labeled TCSPND4 is closest to the UT, and offers the best comparison. The standard deviation of the UT temperature is ~2°C at the maximum test temperatures.

Future Activities

The results of testing to date have been very promising, but some work remains in order to consider the UT completely qualified for in-core deployment. The issue observed in the ULTRA2 test is likely due to changes made to a ceramic cement used to fill the transducer housing, but this has not been verified through PIE. This issue may be solved by identifying a better potting compound or by making the coil wire more robust, either by changing materials or wire diameter.

A planned NSUF-sponsored irradiation test, DISECT, will be performed in the Belgian BR2 reactor in collaboration with Studiecentrum voor Kernenergie/Centre d'Étude de l'énergie nucleaire (SCK•CEN). DISECT is meant to study metallic fuel foils arranged along a ~1 meter test vehicle. Multi-point temperature measurements along the length of the DISECT capsule are needed in order to fully characterize the experiment. Multipoint thermocouples are planned as primary instrumentation, but an INL UT will also be included in the test, along with a promising fiber-optic sensor. The expected temperatures are relatively low for a UT, less than 300°C for the first phase of testing, but the need for a temperature-profile measurement makes the test ideal for demonstration of the performance of the UT because the temperatures measured by the single UT can be directly compared to those of the multipoint thermocouples. The UT designed for this application will have 10 measurement zones along the length of the test, making this the most complicated irradiation yet for the sensor.

This article documents the development of a multipoint ultrasonic thermometer and the progress, to date, toward regular deployment in irradiation experiments. The largest hurdle a new in-core sensor must overcome to be considered qualified is demonstration in prototypic irradiation conditions. The reactor access provided by NSUF has been critical in progressing the UT through several stages of design improvement, and has shown that the UT is a viable option for making multipoint temperature measurements in extreme irradiation environments such as those experienced in the ATR.

Publications

[1.] B. G. Kim, J. L. Rempe, J-F Villard, and S. Solstad, "Review of Instrumentation for Irradiation Testing of Fuels and Materials," Nuclear Technology, 176, p 155-187, 2011.

[2.] M. Laurie, et al., "Ultrasonic High Temperature Sensors: Past Experiments and Prospective for Future Use," Proc. International Symposium on Temperature and Thermal Measurements in Industry and Science (TEMPMEKO), Portorož, Slovenia, June 2010.

[3.] E.P. Papdakis, L.C. Lynnworth, D.R. Patch, E.H. Carnevale, "Ultrasonic Thermometry in LMFBR Systems," Final Report NYO-3906-13, Panametrics Inc. 1972.

[4.] H.A. Tasman, M. Campana, D. Pel, J. Richter, "Ultrasonic Thin-Wire Thermometry for Nuclear Applications," Temperature: Its Measurement and Control in Science and Industry, Vol. 5, Part 2, pp. 1191-1196, 1982.

[5.] L.C. Lynnworth, E.H. Carnevale, M.S. McDonough, S.S. Fam, "Ultrasonic Thermometry for Nuclear Reactors," IEEE Transactions on Nuclear Science, Vol. NS-16, 1968, pp. 184-187.

[6.] J. Daw, J. Rempe, S. Taylor, J. Crepeau, and S.C. Wilkins, "Ultrasonic Thermometry for In-Pile Temperature Detection," Proceedings of NPIC&HMIT 2010, 2010.

Distributed Partnership at a Glance

NSUF and Partners	Facilities and Capabilities
Massachusetts Institute of Technology	Nuclear Reactor Laboratory
Collaborators	
Idaho National Laboratory	Joshua Daw (principal investigator)