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DEVELOPMENT OF A NOVEL ULTRASONIC TEMPERATURE PROBE FOR LONG-TERM MONITORING OF DRY CASK STORAGE SYSTEMS

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ABSTRACT. With the recent cancellation of the Yucca Mountain repository and the limited availability of wet storage utilities for spent nuclear fuel (SNF), more attention has been directed toward dry cask storage systems (DCSSs) for long-term storage of SNF. Consequently, more stringent guidelines have been issued for the aging management of dry storage facilities that necessitate monitoring of the conditions of DCSSs. Continuous health monitoring of DCSSs based on temperature variations is one viable method for assessing the integrity of the system. In the present work, a novel ultrasonic temperature probe (UTP) is being tested for long-term online temperature monitoring of DCSSs. Its performance was evaluated and compared with type N thermocouple (NTC) and resistance temperature detector (RTD) using a small-scale dry storage canister mockup. Our preliminary results demonstrate that the UTP system developed at Argonne is able to achieve better than 0.8 °C accuracy, tested at temperatures of up to 400 °C. The temperature resolution is limited only by the sampling rate of the current system. The flexibility of the probe allows conforming to complex geometries thus making the sensor particularly suited to measurement scenarios where access is limited.

Keywords: Dry Cask Storage System, Ultrasonic Temperature Probe, Long-term Temperature Monitoring
PACS: 43.20.Mv, 43.35.Yb, 43.35.Zc, 43.38.Ct

INTRODUCTION

As a standard procedure, spent nuclear fuel (SNF) of nuclear reactor is initially stored in specially designed pools, Spent Fuel Pools, at individual reactor sites, then transferred to waste depository. Starting from 1985, Dry Cask Storage Systems (DCSSs) for Spent Nuclear Fuel (SNF) have been in use to meet the shortage of wet storage utilities. A DCSS keeps the long cooled SNF dry and stores it in an inert atmosphere. The systems come in various designs of metal and concrete casks intended for on-site storage. By the end of 2010, the U.S. inventory of SNF was over 60,000 metric tones of uranium [1]. About one quarter of the SNF is stored in DCSSs and this ratio will only increase with time.

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With the recent cancellation of the Yucca Mountain repository and no clear path forward for SNF disposition emerging from the draft report of the Presidential Blue Ribbon Committee on America's Nuclear Future [2], potentially much longer times (100-300 years) of dry storage must now be envisioned for SNF before final disposition. Accordingly, the U.S. Nuclear Regulatory Commission (NRC) issued the guidance on the aging management of dry storage facilities that indicates the necessity to monitor the conditions of DCSSs over extended periods of time [3]. As a storage system for SNF, it is important and necessary to keep monitoring its operation to avoid any incidents. Especially, the in-situ and real time monitoring of some crucial physical parameters of DCSSs such as temperature. The change in temperature has been widely used as an indicator of the SNF status and the integrity of the cask in general because fuel failure and cask leakage are always accompanied with sudden temperature increase [4].

The difficulties in monitoring temperature of DCSSs for SNF stem mainly from geometrical restrictions and potential local harsh environments including nuclear radiation. Thermocouple (TC), such as Type K and Type N, is the most commonly used method for temperature measurements. However its application is limited by shunting error [5] and drift [6] as environmental temperature changes. Furthermore, thermocouples only provide measurement at a single location.

In this work, we present a study on continuous temperature monitoring of a dry cask canister mockup using an ultrasonic temperature probe (UTP). Its capability for temperature profiling using a single probe is demonstrated at temperatures of up to 400 °C. A resolution of 0.79 °C has been achieved and its flexibility makes it particularly suited for complex geometries and for scenarios which access to the structure or component is limited.

EXPERIMENTAL SETUP

The UTP technique, shown in Fig. 1, is based on the principle that the sound velocity in all materials is a function of the temperature. The travel time (time of flight or transit time) of ultrasonic signal is temperature dependent. The UTP consists of a magnetostrictive transducer (MST) and a thin magnetostrictive metal probe sectored by notches. The probe, 0.635 mm in diameter and 60 cm in length, is a cobalt/iron alloy, which is different from the conventional materials such as Thoriated Tungsten and Rhenium [7,8]. The MST is a simple electrical coil that generates a magnetic field causing the magnetostrictive probe to contract or elongate. In operation (pulse-echo mode), the coil is energized with 200 kHz pulses to generate longitudinal waves of ~ 2.6 cm in wavelength propagating down the probe.

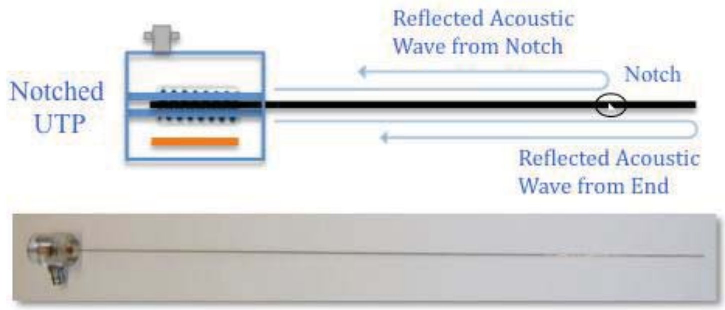

FIGURE 1. Ultrasonic Temperature Probe.

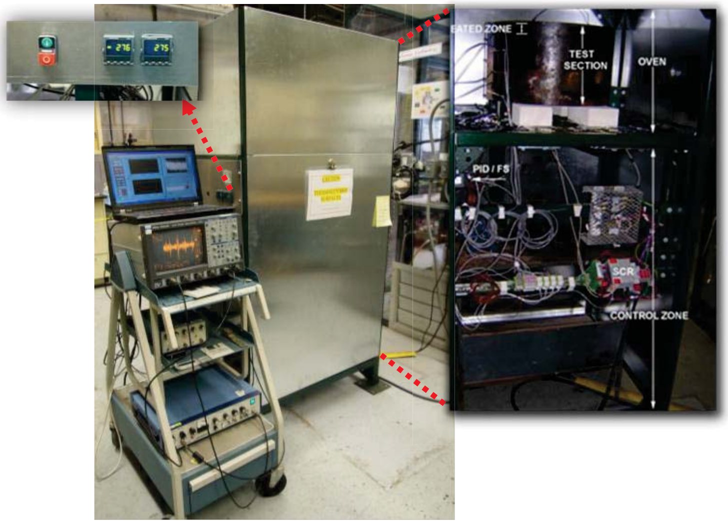

FIGURE 2. Dry Cask Simulation Test Stand with and without protection cover.

As the wavelength is much longer than the probe diameter, these cylindrically guided longitudinal waves [9] behave like surface waves (Lamb waves) with minimal attenuation. As the acoustic wave propagates along the probe, a fraction of the pulse energy is reflected by each discontinuity, such as notches, bending points, and the end surface. These echoes can be used to monitor the local temperatures and consequently the temperature profile.

The attenuation of the acoustic wave in the probe can be estimated from the multi-trip echoes. For the selected probe material, the estimated value is ~1.9 dB/m [10], which provides enough energy to effectively profile and monitor the temperature of DCSS. Furthermore, because the probe diameter is less than one tenth of the acoustic wavelength [11], the wave dispersion effect in the probe is negligible, which ensures a clean signal (high signal-to-noise ratio) for temperature measurements. In addition, the signal attenuation through the probe used in this work is negligible, when the bending angle of the probe is less than 80°, which makes it the ideal technique to monitor the temperature gradient around the circumference of DCSS canister. A mock-up test facility was established at Argonne to evaluate the developed UTP for in-situ temperature monitoring of DCSS metal canisters. The Dry Cask Simulation Test Stand is a structural metal (Unistrut) frame with insulated sheet metal walls. Figure 2 shows the test stand with protection covers in place, which prevent the operating personnel from contacting thermally hot surfaces and/or electrical hardware when the mockup is under test. The test stand with several covers removed is shown on the side. As shown in that figure, the frame is divided into two sections: the top section houses a dry cask simulator, heating element, process thermocouples and calibrated temperature probes; the bottom section houses temperature and power control equipment.

The DCSS mockup is designed to operate at temperatures up to 650°C using a 7 kW heating element. Airflow dampers, heat shields and insulating materials allow gross control over convection and radiation heat losses. It is designed to conduct continuous (24/7), unattended operation at temperatures of up to 300°C and temperature ramping up to 650°C to monitor the aging process and stability of the applied sensors including UTP. As shown in Fig. 2, the canister mockup is comprised of an 11-inch long, 18-inch diameter, mild-steel pipe section with a 1-inch thick wall. It is isolated from the metal frame by furnace insulating blocks (fire brick) and oriented to promote an axial temperature differential.

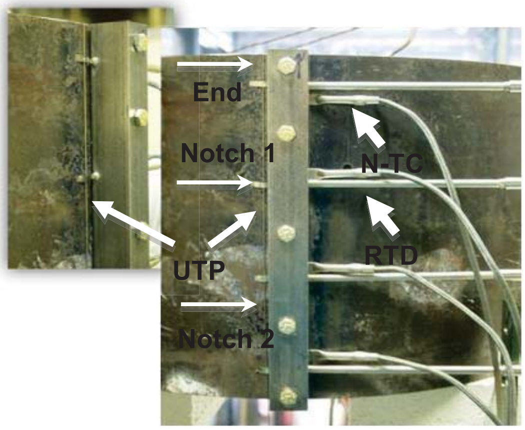

FIGURE 3. The relative positions of notches on the UTP in straight conformation setup to measure temperature profile along the axial direction.

The canister mockup is instrumented with four NTCs (OMEGA, accuracy: ±2.2 °C or ±0.75%) paired with four, 100-ohm RTD probes (OMEGA, accuracy: ±1.8 °C at 300 °C) arranged axially. Type-N TCs exhibit better stability than traditional type E, J, K and T, base-metal thermocouples. The calibrations of the type-N thermocouples and RTDs are NIST traceable. The ultrasonic temperature probe (UTP) is mounted next to the NTCs and RTDs to compare their performance in parallel.

RESULTS AND DISCUSSION

To demonstrate the ability of the UTP sensor to provide temperature profile with a single probe, a probe with two notches (15 cm separation) was used in the experiment. Figure 3 shows the approximate locations of the two notches on the UTP. The first notch was placed at the same elevation as the second NTC/RTD set (from top). The second notch was placed at an elevation in between the third and the fourth NTC/RTD set. The measured ultrasonic echoes from specific locations including the end and the two notches are shown in Fig. 4. In the Time of Flight (ToF) results, the first echo is from the second notch, the second echo is from the first notch, and the third echo is the reflected signal from the end of the UTP. The intensities of echoes are mainly determined by the reflecting area at the measured locations. At the end of the UTP, all incident ultrasonic signals will be reflected back, therefore, the echo from end has the strongest intensity. Additional echoes observed in Fig. 4 after 250 μs are the result of multi-trip reflections along the wire. Higher order reflections that represent contribution of multiple echoes from different locations are not used here for temperature and temperature gradient measurements.

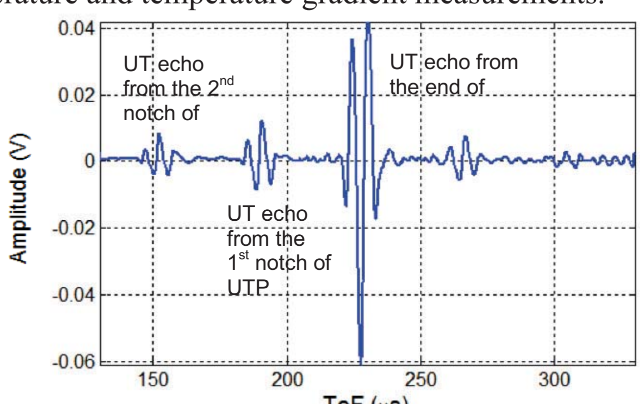

FIGURE 4. Time-of-flight measurement of ultrasonic echoes from specific locations on UTP at 20°C.

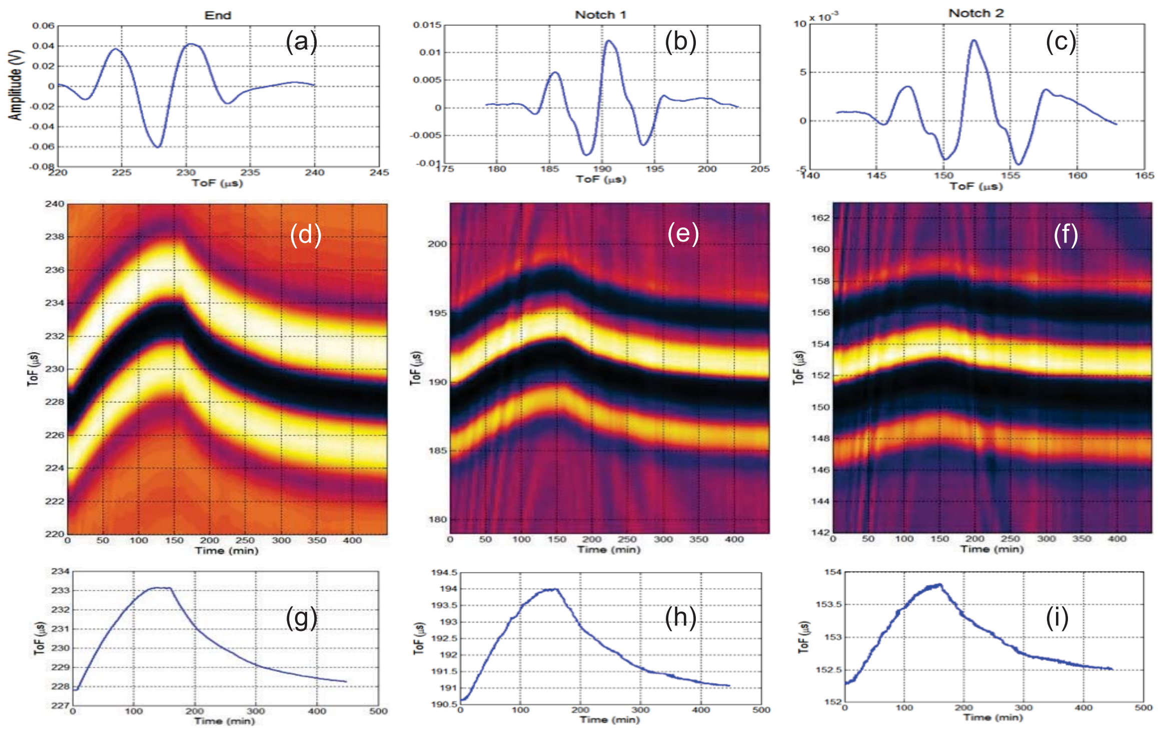

FIGURE 5. Data collected as the UTP in straight conformation from 20°C to 400 °C. (a)-(c) Ultrasonic echoes from the end and two notches at 20°C; (d)-(f) Evolution of the ultrasonic echoes from the end and two notches during heating (ToF increasing) and cooling (ToF decreasing) period; (g)-(i) Evolution of the peak with maximum intensity of the ultrasonic echoes during heating (ToF increasing) and cooling (ToF decreasing) period.

Figures 5(a)-(c) shows the enlarged ultrasonic echoes from the end and the two notches of the UTP. As expected, the signal intensity decreases from (a) to (c). During heating periods, the echoes will shift toward higher ToF values due to the elongation of the probe and the decrease in sound velocity inside the wire at higher temperatures. Conversely, the echoes will shift back during the cooling period. However, because of the difference between heating and cooling rate, the evolution of ultrasonic echoes have different behaviors during those periods, as shown in Figs. 5(d)-(i). The image plots of ToF versus time shown in Figs. 5(d)-(f) display the temporal evolution of the entire echo (peak and side lobes) within a fixed ToF window from the three locations (notches and the end) along the UTP. For a better presentation of the trend, the evolution of the peak intensity from ultrasonic echoes is plotted out separately in Figs. 5(g)-(i). The measured temperature with the RTDs and the NTCs are shown in Figs. 6 (a) and (b). Comparison of data in Figs. 5 and 6 indicates that the measurements made by UTP show the same trend as those made by both RTDs and NTCs. Based on the sampling rate of the system, the total shift in ToF, and the tested temperature range, the resolution for temperature measurement using our current UTP is 0.79 °C, which is better than that of NTCs used in the experiment and comparable to the that of RTDs.

It is important to note that the resolution for measuring the subtle changes of ToF is limited only by the sampling rate of the current system. While the resolution of current UTP system is considered acceptable for the application at hand, if necessary, it could be further increased to measure even smaller changes of ToF by employing an acquisition configuration with a higher sampling rate. Furthermore, the UTP technique depends on density and elastic properties of the selected probe material and not on its electrical properties. Therefore it avoids the need for high temperature electrical insulating material that is required by TCs used for high temperature measurements.

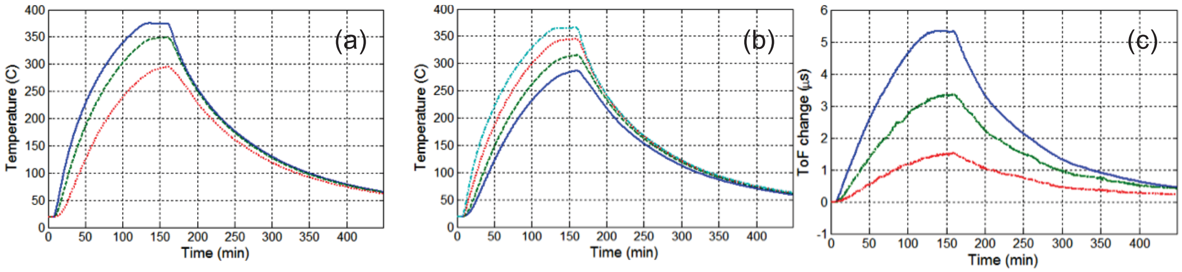

FIGURE 6. Data collected as the mockup heated from 20°C to 400°C with straight UTP conformation. (a) RTD data, (b) thermocouple data, and (c) UTP data.

The test results using a straight UTP conformation design with two notches are shown in Fig. 6. Data for those tests were collected while the canister mockup was heated up (to 400°C) and cooled down (to 20°C). The measurements made simultaneously using the RTD and NTC sensors are provided in Figs. 6(a) and (b), respectively. Fig. 6(c) is a composite plot of data shown in Fig. 5. For the temperature range tested here, the UTP results show the same trend as seen in the RTD and the NTC data and with even higher degree of accuracy.

In addition to good accuracy, the flexibility of the UTP provides an important advantage over other temperature sensors as the surface-conforming wireline probe allows measurements to be made over complex geometries. This renders the probe particularly suitable for measurement scenarios where access is limited. To demonstrate this capability, the flexible wireline probe was bent and placed diagonally along the outside surface of the canister mockup, as shown in Fig. 7. The corresponding locations of notches along the contoured probe are also highlighted in that figure. The magnetostrictive transducer (MST) used in the experiment is shown as inset. To more realistically simulate challenging field scenarios involving confined spaces and limited access, the wireline probe was fed through a small opening at the bottom of the test stand. It is worth noting that in practice, the MST could be placed at much longer distances from the test piece, which helps minimize any potential long-term damage to the sensor's electronics.

The experimental data collected using the contoured UTP configuration is shown in Fig. 8. The results in general demonstrate that the UTP performs properly even under bending deformation. The probe can be modified into different shapes such as ribbon and tube for specific applications. In this experiment, a rapid cooling ramp was purposely introduced to test the response time of the UTP. As highlighted in Figs. 8(g)-(i), the rapid change in cooling rate was clearly picked up by the UTP.

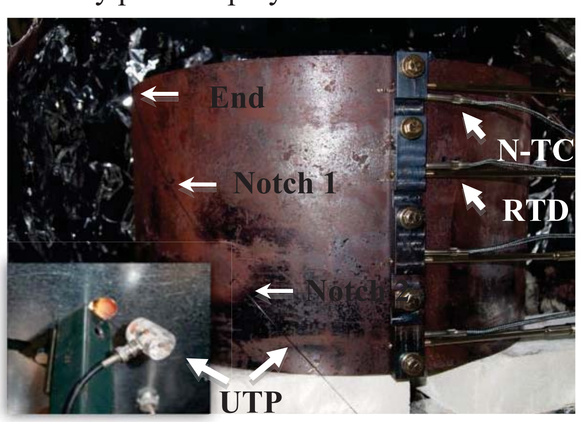

FIGURE 7. The approximate position of notches on the UTP in contoured conformation setup.

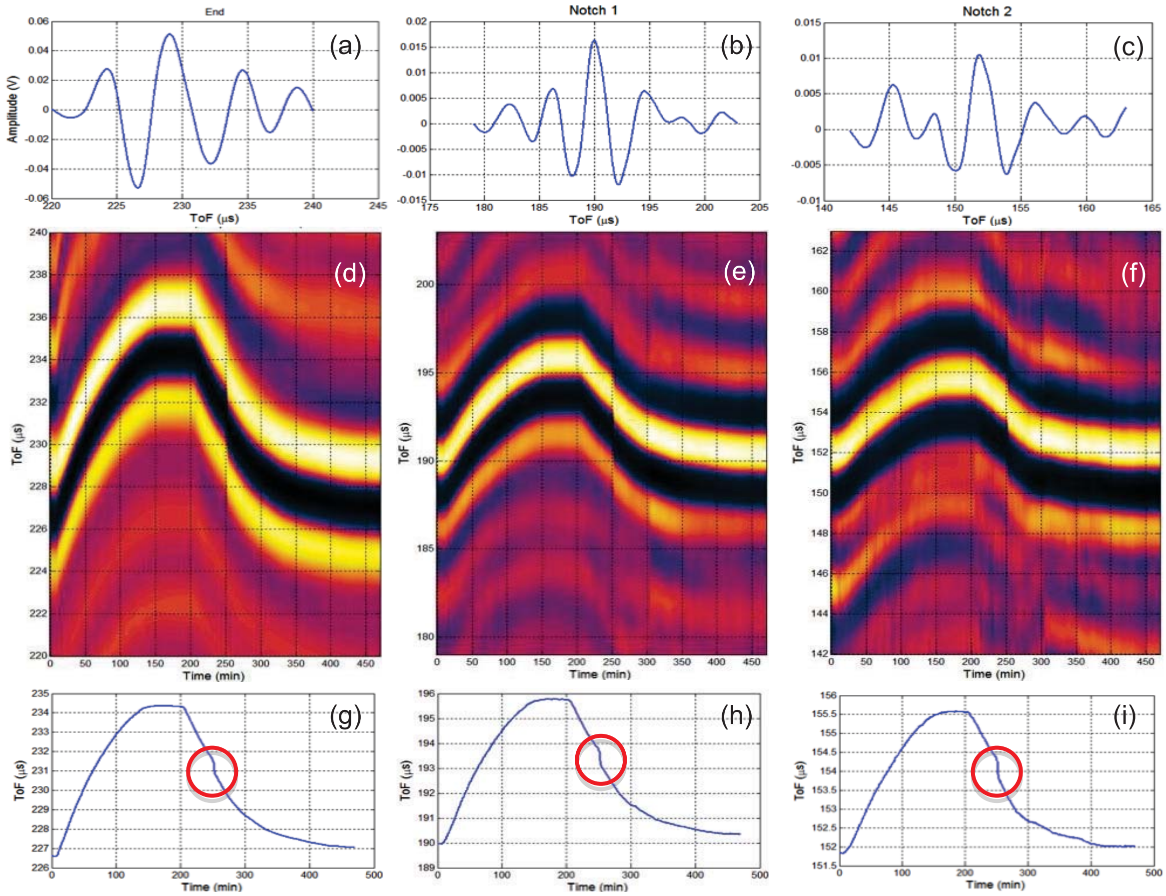

FIGURE 8. Data collected with the UTP in bending conformation setup over a temperature of 20°C to 400 °C. (a)-(c) Ultrasonic echoes from the end and two notches at 20°C; (d)-(f) Evolution of the ultrasonic echoes from the end and two notches during heating (ToF increasing) and cooling (ToF decreasing) period; (g)-(i) Evolution of the peak with maximum intensity of the ultrasonic echoes during heating (ToF increasing) and cooling (ToF decreasing) period. The circles mark the location of the rapid cooling ramp detected by UTP.

The test results using the contoured UTP with two notches are shown in Fig. 9. The data was collected as the mockup was heated up (to 400°C) and cooled down (to 20°C). The measurements from RTDs and NTCs are provided in Figs. 9(a) and (b), respectively. Figure 9(c) shows the UTP results over the tested range of temperature. The temporal data once again demonstrate that the UTP response closely follows that of RTD and NTC, including at the zone associated with rapid cooling ramp. Based on the results of the investigations conducted so far, the performance of the UTP developed under this work demonstrates the unique advantage of this technology for long-term monitoring of DCSS condition.

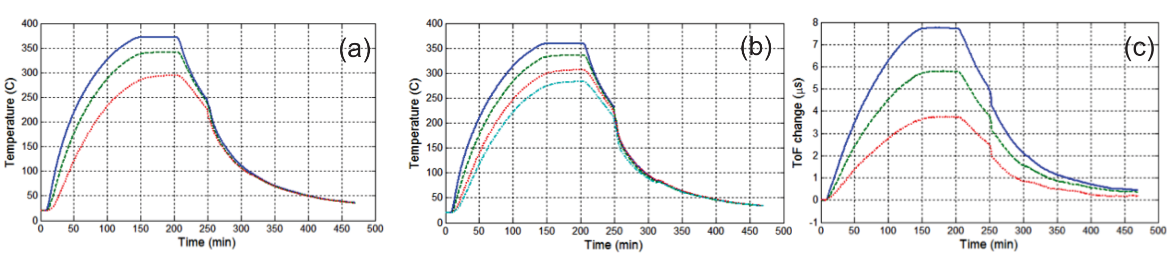

FIGURE 9. Data collected with the bent UTP conformation setup as the mockup was heated from 20°C to 400°C. Shown here are (a) RTD data, (b) Thermocouple data, and (c) UTP data.

CONCLUSIONS

Using special material and UTP design, we have demonstrated a simple, reliable, small size, and low cost sensor for the continuous temperature monitoring of DCSSs with a measurement accuracy of 0.79 °C. The UTP system developed in this work obviates a number of limitations inherent to TC type devices. The primary advantages of the UTP sensor include the robustness of the probe for long-term monitoring under extreme conditions, the ability to obtain temperature profile with a single element, the surface conforming nature of its flexible probe allowing measurements over complex surfaces and in confined spaces, and adaptability to monitoring of existing DCSSs. The weld-free installation of the probe makes it even more attractive for monitoring of existing DCSSs. Its applications can be further extended to other scenarios with complex geometries and limited access. Efforts are presently underway to extend the above technique to measure other parameters of interest than temperature, such as integrated radiation flux.

ACKNOWLEDGEMENTS

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