

## Development and Demonstration of Ultrasonic Under-Sodium Viewing System for SFRs

Hual-Te Chien, Thomas Elmer, David M. Engel, and William P. Lawrence

Argonne National Laboratory, Argonne, IL USA

*E-mail contact of main author: htchien@anl.gov*

### Abstract

Argonne National Laboratory (ANL) has successfully developed ultrasonic waveguide transducers (UWTs), brush-type ultrasonic waveguide transducers (BUWTs), and submergible transducers that can be used for defect detection, component identification, loose part location, and operation monitoring in the harsh sodium environment. An under-sodium viewing (USV) facility was constructed for the development and in-sodium testing of instruments and nondestructive evaluation techniques that potentially could be used for SFRs. An integrated USV imaging system, including data acquisition, signal and imaging processing, and different automated scanning mechanisms, was developed for real-time and faster defect detection and visualization. Prototypes of UWTs and high-temperature submergible transducers were tested successfully in water, hot oil, and sodium. The UWTs showed a detection resolution of 0.5mm in width and depth, respectively, and also demonstrated component recognition capabilities in sodium up to 343°C. The high-temperature submergible transducer prototypes demonstrated a detection resolution of 1mm in width and 0.5mm in depth in sodium up to 343°C. Brush-type ultrasonic waveguide transducers (BUWTs) were also developed to reduce inspection/imaging time. Multiplexing technique was tested in a water mockup and has shown great defect detection capability. Argonne is currently integrating the BUWT and phased array (BUWT-PA) techniques for better deflection resolutions and faster inspection. Feasibility study of BUWT-PA is in progress. The future R&D plan for a USV system is also presented.

**Key Words:** Under-sodium Viewing, USV, Ultrasonic Waveguide Transducer, Sodium-submergible Ultrasonic Transducer.

### 1. Introduction

An under-sodium viewing (USV) system will be an essential instrument for real-time monitoring of core operation and/or in-service inspection of components, structures, and systems within the reactor core or steam generators of an SFR. The USV system must be capable of operating in the high-temperature, high-radiation, and corrosive environment of liquid sodium. Also, a viable USV system must rely on ultrasonic imaging because liquid sodium is optically opaque and electrically conductive. Argonne National Laboratory (ANL) has successfully developed ultrasonic waveguide transducers (UWTs), brush-type ultrasonic waveguide transducers (BUWTs), and submergible transducers to overcome these major technical challenges in developing a USV system. The Argonne USV system can be used for defect detection, component identification, loose part location, and operation monitoring in the harsh sodium environment. A USV facility was constructed for the development and in-sodium testing of instruments and nondestructive evaluation techniques that potentially could be used for SFRs. An integrated USV imaging system, including data acquisition, signal and imaging processing, and different automated scanning mechanisms, was developed for real-time and faster defect detection and visualization.

Argonne has constructed UWT prototypes that consist of special designed waveguides to isolate conventional ultrasonic transducer from the harsh core environment of SFRs. These prototypes have shown high detection sensitivity with minimal background noise by effectively reducing spurious echoes and mode conversions. The technology has demonstrated a real-time, in-sodium defect detection capability with detection resolutions of 0.5mm in both width and depth in sodium at elevated temperatures up to 343°C. Prototypes of high-temperature submergible transducer were also developed and tested successfully in water, hot oil, and sodium. Different piezoelectric elements and backing materials were evaluated. The prototypes have demonstrated a detection resolution of 1mm in width and 0.5mm in depth in sodium at elevated temperatures up to 343°C. Both technologies have also shown a great capability of recognizing components with 3D geometries, such as rods, cubes, and spheres.

To reduce imaging time, we have also developed BUWTs. Multiplexing technique was tested first. The results generated from water mockup have shown great defect detection capability. Argonne is currently integrating the BUWT and phased array (BUWT-PA) techniques for better deflection resolutions and faster inspection. Feasibility study of BUWT-PA was conducted in water and preliminary results have shown that the inspection speed is 10 times faster. However, the resolutions of BUWT-PA are not as good as that of the UWTs and submergible transducers. The future USV R&D works are also presented.

## **2. Ultrasonic USV System Development**

The optimal goal is to develop an ultrasonic USV system that has high defect-detection resolution and is able to provide rapid in-service inspection of reactor core and mechanical components in SFRs. Usually, inspection works are conducted during shutdown while sodium temperature is between 200°C and 260°C. The major technical challenge in developing a USV system is the design of a transducer that can sustain the high-temperature, high-radiation, and corrosive environment. Two approaches being pursued are high-temperature transducer development [1-4] and use of a waveguide [5-7].

### **2.1. Ultrasonic Waveguide Transducers (UWTs)**

Waveguides have been used for years to deliver and receive sound waves in a hostile environment. A waveguide acts as a buffer rod that isolates the sensing transducer from a high-temperature and corrosive medium. The ideal UWT must have high efficiency as a transmitter and high sensitivity as a receiver. In practice, the problem with using a waveguide to transmit ultrasonic waves is the presence of spurious echoes resulting from mode conversion, wave dispersion, reverberation, and diffraction within the waveguide. Elimination or reduction of the spurious echoes is the main consideration in waveguide development. After the evaluation of various types of waveguide designs, Argonne has designed a hybrid UWT, shown in Figure 1, which is composed of bundle and spiralled-sheet rods [7]. It consists of a cylindrical shape waveguide with a focus lens welded on one end and a PZT transducer bonded at the other end. Waveguides of different lengths (6", 12", and 18") and diameters (5/8" and 11/16") were constructed for evaluation. Figure 2 shows the receiving ultrasonic radio frequency signals received from smooth, threaded, bundle-rod, and Argonne UWT waveguides in water. The UWT prototype shows high detection sensitivity with minimal background noise by effectively reducing spurious echoes and mode conversions.

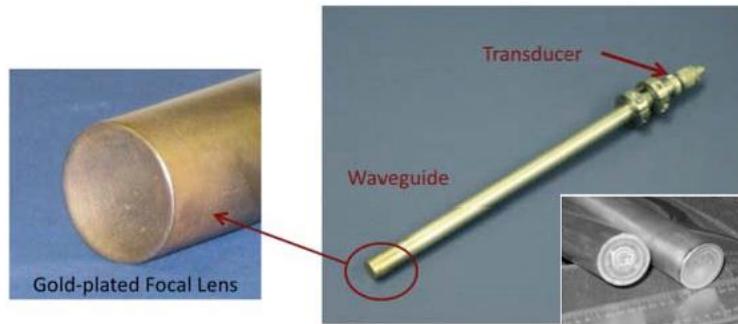


FIG. 1. A UWT Prototype with a 1" focal lens.

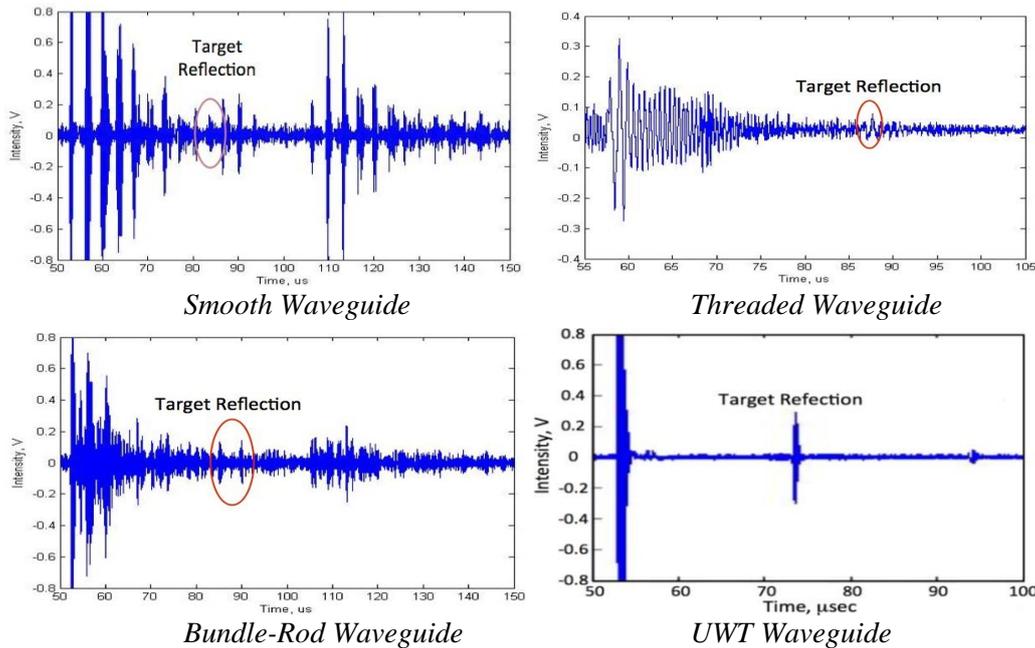


FIG. 2. Ultrasonic radio frequency signals received from smooth, threaded, bundle-rod, Argonne UWT waveguides in water.

## 2.2. Submersible Ultrasonic Transducers

Typically, commercial high-temperature ultrasonic transducers are fabricated by applying a high-temperature bonding material or by welding to bond a piezoelectric element onto the front surface of the transducer housing. However, the bonding often fails due to the thermal expansion coefficient differences between the bonding material, transducer housing, and piezoelectric material. Instead, Argonne has developed sodium-submersible transducers using a mechanical compression mechanism to couple a piezoelectric element onto the focal lens to ensure consistent bonding at elevated temperatures and under thermal cycling [8].

Four high-temperature submersible transducer prototypes were fabricated. Two of them consist of PZT-5A crystal, and the other two use  $\text{LiNbO}_3$ . Each prototype consists of a focal lens made of either SS or nickel. The focal lens has a focal distance (FD) of 25.4mm. The lens was then welded onto a SS transducer housing. All of the transducers are 28.58mm in diameter and 50.8mm in length and have an operating frequency at 2.25 MHz. Each prototype uses a mechanical compression mechanism to ultrasonically couple a crystal to the focal lens. A backing material is attached to the back surface of the crystal to minimize the crystal ringing. The selected backing materials must be highly attenuating ultrasonically and stable at elevated temperatures and under thermal cycling. Several potential candidates of backing

materials were identified and evaluated. Figure 3 shows the first high-temperature submersible PZT-5A prototype that was completely sealed after an SS cap was welded onto it, as well as the second prototype before cap welding.



FIG. 3. High-temperature submersible PZT-5A prototypes: (left) prototype #1 after complete sealing and (right) prototype #2 before sealing

### 2.3. Under-Sodium Viewing (USV) Test Facility

A USV test facility, shown in Figure 4, was constructed for the evaluation and validation of the UWT technology. The facility includes three primary subsystems: a sodium loop, an enhanced heating and temperature control system, and a scanning and data acquisition (S&DAQ) system. The sodium loop consists of a test tank, a dump tank, an electromagnetic pump, a flow meter, and a cold trap. The electromagnetic pump circulates sodium, and the cold trap removes impurities, such as sodium hydroxide and sodium oxides, in the sodium. The heating and control system is capable of heating the sodium loop up to a temperature of  $>350^{\circ}\text{C}$  with precise temperature control. The S&DAQ system controls a scanning system and conducts data acquisition and image processing to provide a real-time C-scan image.



FIG. 4. Argonne USV test facility.

### 2.4. In-sodium Experimental Setup

Two ports on the test tank cover flange are designated for mounting of a target (the rectangular port) and testing of a UWT prototype (the circular port). To facilitate scanning capability and avoid sodium leak and contamination, a bellows mounting assembly was designed and constructed to keep the test tank completely sealed while still allowing free movement and the convenience of replacing the transducer. To conduct XY scanning, the bellows mount assembly is firmly linked with an XY-translation system through three high-

strength index rods welded to the bellows top plate. A UWT is mounted through the Swagelok connector on the top plate and aligned with the center of the target mounted in the target port. Figure 5 shows an in-sodium experimental setup of a UWT.

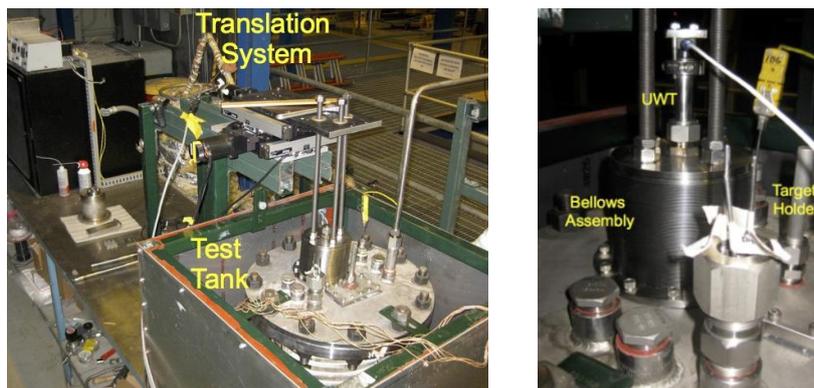


FIG. 5. Experimental setup with a bellows mounting assembly of a UWT.

## 2.5. S&DAQ System and Improvement

An S&DAQ software, running on LabView<sup>®</sup> platform, was developed to automate the USV system, reduce scanning time, and rapidly generate and enhance images from raw data. The system is able to automatically calculate an optimal scanning speed based on the moving average number and scanning resolution set by an operator. The system is also capable of generating a real-time ultrasonic intensity image from results of the total energy of the moving average of ultrasonic A-scan signals while scanning and in much less time than earlier with the implement of a new continuous scanning mode and a moving average technique. An enhanced post-processing software, running on Matlab<sup>®</sup> platform, was developed for an advanced signal and imaging of raw data for better defect detection or component recognition.

## 3. Experimental Results

A series of USV tests were conducted using USV, fuel-pin, Joyo-pin, and ball-bearing target samples to evaluate resolutions, beam size, focal effect, and geometric effect for defect detection or component recognition of the UWT and the sodium-submersible ultrasonic transducer technologies.

### 3.1. In-sodium Tests of UWT

#### Ball-bearing Target Sample

According to ASTM E1065–08, a ball-bearing target sample was designed and two identical target samples were fabricated. A series of in-sodium tests were conducted first to determine the beam diameters and shapes of the UWT at the focal point (FD = 25.4mm) and at various distances from the focal point. This study led to a better understanding and explanation of focal effect on defect detection resolution and component detection and recognition capabilities, especially for a component with a complex 3D geometry. Figure 6 shows the target sample and real-time, in-sodium images (dimensions: 25.4mm × 25.4mm and resolution: 100 × 100 pixels) of the target generated at 177°C and at different distances (FD). The images show that the ultrasonic beam diameter converges in near field and reaches the minimum size (~6.5mm) at the designed focal point (FD = 25.4mm). Beam diameter then increases when traveling into far field. These images also show that the beam retains its round shape from near to far field.

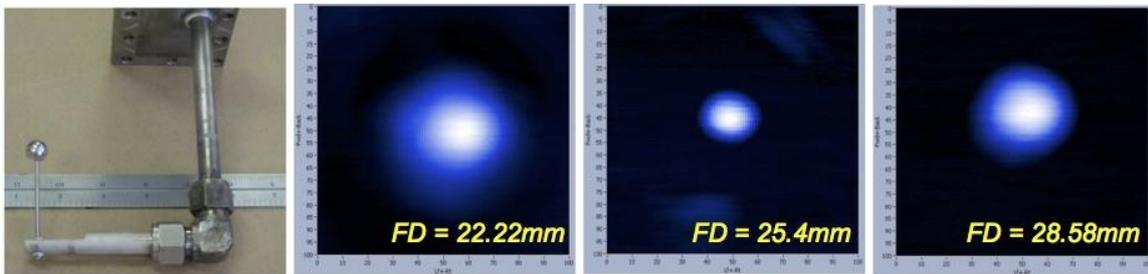


FIG. 6 Ball-bearing target sample and beam diameter images of target sample at 177 °C.

### USV Target Sample

A USV target sample was designed and fabricated for the evaluation of defect-detection capabilities, such as minimum detectable defect size and depth, of the USV system. Figure 7 shows the USV target sample and real-time TOF and intensity images of the USV target, 100 × 100 pixels scanning resolution, in sodium at a temperature of 177°C and FD = 25.4mm. A sharp and clear image of the three letters “USV” was generated. We were able to achieve an in-sodium defect detection resolution of 1mm in width and 0.5mm in depth through intensity imaging and 0.5mm in width and 1mm in depth through TOF imaging in real-time without any signal and image processes.

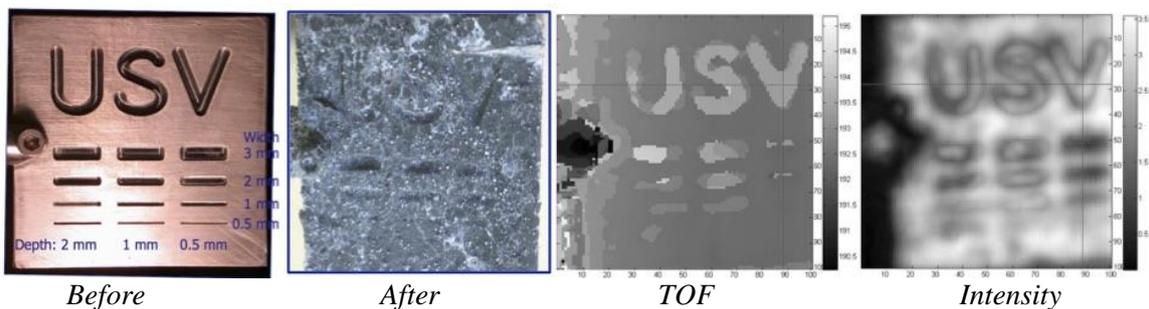


FIG. 7. USV target sample before and after sodium tests and TOF and intensity images of the USV target sample at 177°C and FD = 25.4mm.

### Fuel-Pin Target Sample

A fuel-pin target sample was designed and fabricated for the evaluation of component detection and recognition capabilities of, for example, shape, height, and thickness, of the USV system. The target sample consists of 12 tubes that have exactly the same length (8.89mm) and wall thickness (1.27mm) and a holding nut. Figure 8 shows the fuel-pin target sample and TOF and intensity images, 100 × 100 pixels in scanning resolution, of the target sample after it was submerged in sodium for 4 hours at a temperature of 177°C and FD = 25.4mm. The locations and shapes of the 12 tubes and the nut were clearly identified.

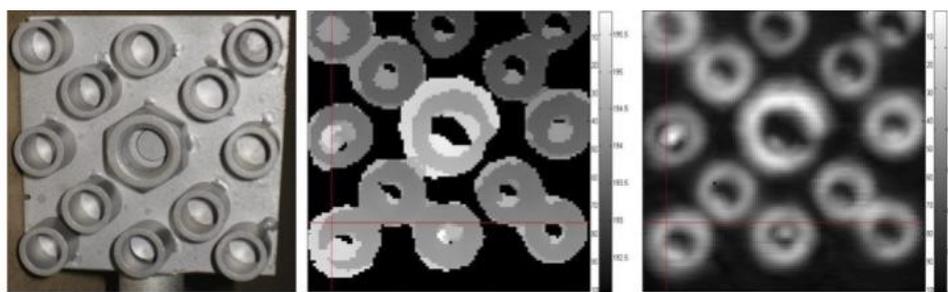


FIG. 8 Fuel-pin target sample (left) and TOF (middle) and intensity (right) images of fuel-pin target sample in sodium at 177°C and FD = 25.4mm.

### Joyo-Pin Target Sample

Through a U.S. Department of Energy-Japan Atomic Energy Agency collaboration, the USV system was proposed for use in locating the small pins believed to reside in the Joyo SFR. A Joyo-pin target sample, consisting of two groups of pin simulants, was designed and fabricated. One group has four Joyo-pins welded with differing tilt angles for the evaluation of the capability of locating a pin that might be positioned differently within the reactor core. The other has three circular pins with different diameters for the evaluation of scanning resolution and focal effects of components with circular or complex geometries. Figure 9 shows the target sample and a real-time intensity image of the sample at 177°C and FD = 25.4mm. Without any signal or image processing and under a low scanning resolution (50 × 50 pixels), the real-time image clearly identifies all of the pin samples of differing tilt angles.



FIG. 9 Joyo-pin target sample before and after sodium tests and intensity image of the target sample at 177°C and FD = 25.4mm.

### **3.2. Evaluation of Submergible Ultrasonic Transducers**

Submergible ultrasonic transducer prototypes consist of either PZT-5A or LiNbO<sub>3</sub> piezoelectric elements with either SS or nickel focal lens were constructed and tested. Each prototype was tested in water first for the optimization of its coupling mechanism and the evaluation of its defect detection sensitivity. Hot oil tests were followed to evaluate their detection sensitivity at elevated temperature. The prototypes then were tested in liquid sodium at an elevated temperature up to 350°C. Additional water test was performed after sodium tests to verified the integrity of the prototype.

#### USV Target Sample

In-sodium tests of a LiNbO<sub>3</sub> transducer prototype with SS focal lens were conducted to evaluate defect detection capability, such as minimum detectable defect size and depth, of the USV system. The prototype was tested in water and then in hot oil up to 160°C to evaluate its performance and stability. Although the operating temperature of LiNbO<sub>3</sub> is around 900°C, the transducer and target was only heated up to 343°C, which is the maximum temperature certificated for the test tank. Figure 10 shows the real-time ultrasonic intensity images generated by the prototype at FD of 38.1mm, 44.45mm, and 50.8mm, respectively, in hot oil at 160°C after the prototype was completely sealed. Detection sensitivities of 0.5mm in both width and depth were achieved even the target sample was located 50.8mm away from the transducer.

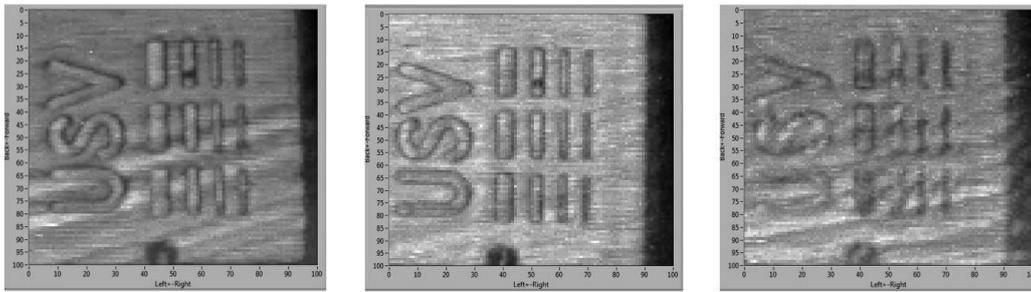


FIG. 10 Real-time intensity images from a  $\text{LiNbO}_3$  transducer prototype for target located at FD of 38.1mm (left), 44.45mm (middle), and 50.8mm (right) in hot oil at 160°C.

For in-sodium tests, the transducer prototype was under thermal cycling daily, being heated up to and maintained at 343°C during the daytime and cooled down to 160°C during the night. After a week, a noticeable reflection signal was received. Figure 11 shows intensity images of the prototype located at different FD in liquid sodium at 326°C. Detection resolution of 0.5mm in width and 2mm in depth was achieved. We also conducted in-sodium tests of a  $\text{LiNbO}_3$  transducer prototype with nickel focal lens and backing material V2. By using a nickel focal lens, the sodium wetting of the transducer was improved and speeded up. As a consequence, the detection resolution was also improved. Figure 12 shows intensity images of the prototype located at different FD in sodium at 326°C. A detection resolution of 0.5mm in width and 1mm in depth was achieved. The detection sensitivity is not as good as expected. It is possible that either the prototype or the target was not fully wetted, or an impurity had appeared on the target and attenuated the ultrasonic signal.

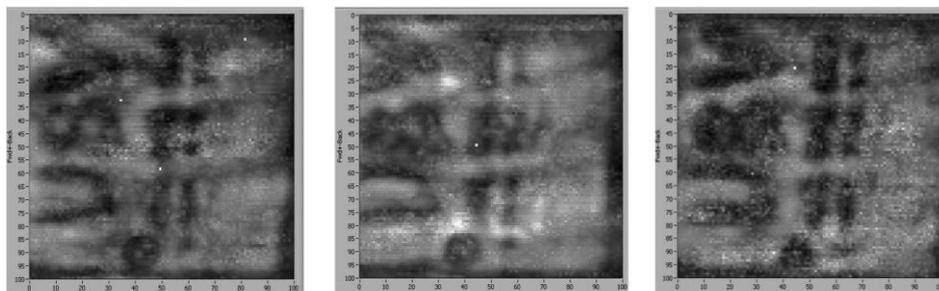


FIG. 11 Real-time ultrasonic intensity images from  $\text{LiNbO}_3$  transducer prototype with SS focal lens at FD of 19.05mm (left), 25.4mm (middle), and 31.75mm (right) in sodium at 326°C

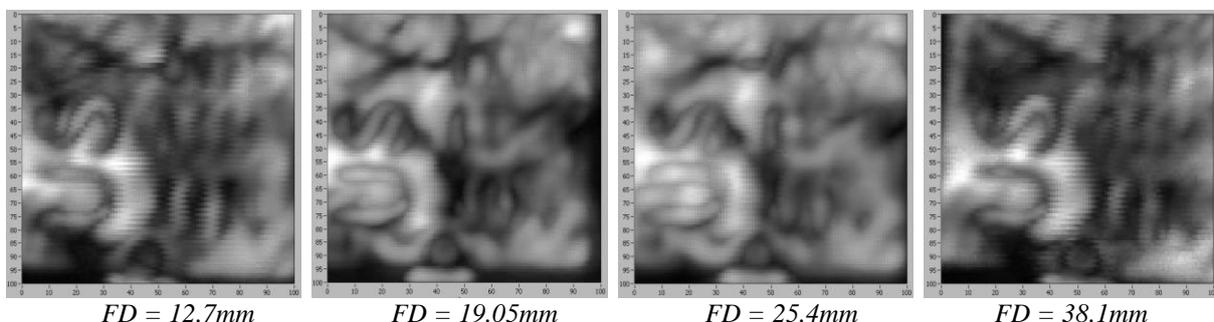


FIG. 12 Real-time ultrasonic intensity images from  $\text{LiNbO}_3$  transducer prototype with nickel focal lens at FD of 12.7mm to 38.1mm in sodium at 326°C

### Joyo-Pin Target Sample

Figure 13 shows real-time intensity images of the Joyo-pin target sample located at different locations (FDs) from the transducer in sodium at 326°C. The images clearly identify all of the pins with different heights, tilt angles, and shapes. This study demonstrated that the USV

system could be used for locating the missing pins in the Joyo SFR. It also showed that the USV system is capable of recognizing circular objects of different diameters.

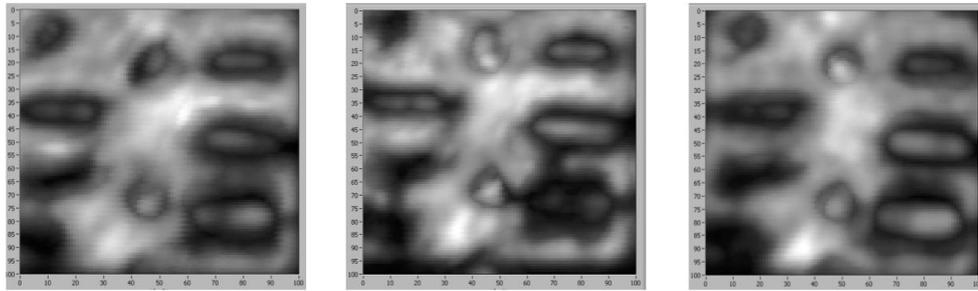


FIG. 13 Real-time ultrasonic intensity images of the Joyo-pin target sample from a  $\text{LiNbO}_3$  transducer prototype at FD of 25.4mm (left), 28.58mm (middle), and 31.75mm (right) in sodium at 326°C.

#### 4. Development of BUWT

The single-transducer USV system relies on two-axis mechanical scanning, which generally is time-consuming, to generate a C-scan image. To be applicable for USV, either the scanning mechanism or the transducer must be further improved. Use of a linear array transducer, such as a BUWT, would allow electronic line scanning and thus reduce the inspection time. Two BUWT prototypes made of SS were constructed and water and hot oil tests were conducted to evaluate the ultrasonic energy attenuation, beam uniformity, and temperature effect. For water mockup tests, an 8- and 32-element PA transducers were fabricated and integrated with a BUWT [9]. An UTPA (Ultrasound Phase Array) simulation package, developed on MATLAB<sup>®</sup> platform, was developed to optimize the beam steering and profile. The package is integrated with a user friendly GUI for inputs of various design parameters and post-processing of wave pattern visualization. Water tests were performed to evaluate if each channel of the eight-element PA is able to deliver enough energy and has an SNR that will produce any reasonable imaging. The crosstalk between adjacent waveguide regions is less than 2%, indicating that its effect on image construction is minimal. Signal attenuation through the waveguide was estimated to be  $\sim 0.78$  dB/in at the operating frequency of 2.25 MHz. Figure 14 shows an integrated 8-element BUWT-PA and the real-time TOF and intensity images of USV target sample generated by using multiplexing technique form a water mock test.

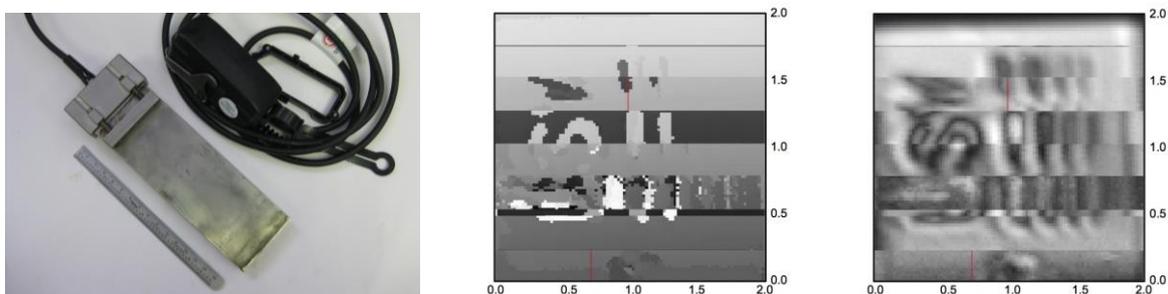


FIG. 14 8-element BUWT prototype (left) and TOF (middle) and intensity (right) images of USV target sample generated by using eight-channel multiplexing technique in water.

Argonne will continue the development and evaluation of sodium-submerged BUWT and innovative BUWT-PA, and ultra-high-temperature (500-800°C) transducers in water, hot oil, and sodium. Work will focus on reliability and probability of detection (POD) with thermal cycling, evaluation of geometry and focal distance effect, and signal and imaging processing methodologies for loose-part detection (beyond the minimal performance requirements

specified for the detection of a Joyo pin). Work also continues to identify improvements in sensor materials to support the ability of these components to work in a high temperature, high radiation, and extreme corrosive environment.

## 5. Conclusions

Argonne has developed a USV system based on the UWT technique and sodium-submersible ultrasonic transducers. Argonne also is exploring and developing BUWT and BUWT-PA technologies for USV and other high-temperature applications. A USV test facility was constructed for evaluation and validation an USV system. Prototypes of UWTs were tested successfully in liquid sodium at temperature up to ~350°C. The technology demonstrated a real-time, in-sodium defect detection capability with detection resolutions of 0.5mm in both width and depth. We also demonstrated that the UWT-USV system is capable of recognizing components with 3D geometries, such as rods, cubes, and spheres and potentially locating lost parts. We have developed sodium-submersible ultrasonic transducer prototypes that consist of different piezoelectric elements, a SS or a nickel focal lens, and different backing materials. In-sodium tests showed a real-time, in-sodium defect detection capability with detection resolutions of 0.5mm in width and 1mm in depth. The results of laboratory in-sodium tests have shown that detection sensitivity is greatly affected by the wetting of the transducers and the targets. The detection capability would be improved in the core environment of a SFR because the sodium is much cleaner, and wetting might not be an issue. The successful deployment of the USV technology will improve reliability, ensure safety, and reduce operational costs for nuclear energy stakeholders.

## Reference:

- [1] Ord, R. N., and R. W. Smith, "Development of an Under-Sodium Ultrasonic Scanner for in-Reactor Surveillance," HEDL-TME 72-91, Hanford Engineering Development Laboratory, Richland, Washington (1972).
- [2] Barrett, L. M., J. A. McKnight and J. R. Fothergill, "Ultrasonic Viewing in Fast Reactor," *Phys. Technol.*, 15, pp.308–314 (1984).
- [3] Takeishi, M., et al, "Development of Multiple Ultrasonic Transducer for Under Sodium Visual Observation," *5<sup>th</sup> Int'l Conf. on Nuclear Eng.-ICON 5*, Nice, France, 26–30 May (1997).
- [4] Karasawa, H., et al, "Development of Under-sodium Three-dimensional Visual Inspection Technique using Matrix-arrayed Ultrasonic Transducer," *J. Nuclear Sci. & Technol.*, 37(9), pp.769–779 (2000).
- [5] Lynnworth, L. C., et al, "Extensional bundle waveguide techniques for measuring flow of hot fluids," *IEEE Trans. Ultrason., Ferroelect., Freq. Control*, 52(4), pp.538–544 (2005).
- [6] Joo, Y.-S., and J.-H. Lee, "Ultrasonic Waveguide Sensor Using a Leaky Lamb Wave for Under-Sodium Viewing," *Rev. of Quant. NDE*, 29, eds. D. O. Thompson and D. E. Chimenti, pp.1013–1020 (2010).
- [7] Wang, K., H.-T. Chien, W.P. Lawrence, D.M. Engel and S.-H. Sheen "Ultrasonic Waveguide Transducer for Under-Sodium Viewing in SFR," *Int'l J. of Nuclear Energy Sci. and Eng.*, 2(2), pp.39–44 (2012).
- [8] H.-T. Chien, D.M. Engel, W.P. Lawrence, and S.H. Sheen, "Complete Array-Waveguide USV System Development, ANL-ARC-297, Argonne National Laboratory, Argonne, IL (2014).
- [9] S.-H. Sheen, H.-T. Chien, W.P. Lawrence, and A.C. Raptis, *Ultrasonic Array Waveguide Transducer for Under Sodium Viewing*, ANL Invention Report, Disclosure No. IN-10-088 (2010).