INL/EXT-19-54981
Revision 0

Integration Testing of Ultrasonic Deformation Sensor for TREAT Experiments

Joshua Daw, Anthony Crawford, Richard Skifton, Lance Hone-INL
Andrew Casella, Matthew Prowant, Chris Hutchinson, Morris Good, Robert Montgomery-PNNL
Pradeep Ramuhalli-ORNL
September 2019

The INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance

INL/EXT-19-54981
Revision 0

Integration Testing of Ultrasonic Deformation Sensor for TREAT Experiments

Joshua Daw, Anthony Crawford, Richard Skifton, Lance Hone-INL
Andrew Casella, Matthew Prowant, Chris Hutchinson, Morris Good, Robert Montgomery-PNNL
Pradeep Ramuhalli-ORNL

September 2019

Idaho National Laboratory
Pacific Northwest National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Office of _______
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Integration Testing of Ultrasonic Deformation Sensor for TREAT Experiments

INL/EXT-19-54981
Revision 0

September 2019

Approved by:

Name Title [optional]	Date
Name Title [optional]	Date
Name Title [optional]	Date
Name Title [optional]	Date

SUMMARY

Fuel deformation (both axial and radial) information provides insights into fuel performance and failure limits. Traditionally, fuel deformation has been quantified using post-irradiation examinations due to the lack of an appropriate sensor for monitoring deformation in situ. Recent developments in sensor and instrumentation design have led to the use of linear variable differential transformers (LVDT) for monitoring axial strain in fuel during irradiation. Size and operational constraints limit the use of LVDT sensors for radial deformation monitoring, and alternatives are needed.

One possible alternative to LVDT sensors is an ultrasonic sensor. Ultrasonic sensors monitor the interaction of high-frequency stress waves with the test object. The resulting response may be analyzed to determine the properties of the material, including stress, strain, microstructure, presence of defects, and the elastic constants. While ultrasonic measurements have been successfully applied for monitoring strain in a number of applications, their use for in-core measurements has been limited. Largely, the limitations are due to the challenges associated with designing sensors that can operate under typical in-core conditions.

This report documents testing performed to confirm that the prototypic ultrasonic deformation sensor can be integrated into TREAT irradiation experiments using the SETH capsule.

CONTENTS

FIGURES

TABLES

ACRONYMS

AlN	Aluminum Nitride
BiT	Bismuth Titanate
DOE-NE	Department of Energy-Nuclear Energy
LVDT	Linear Variable Differential Transformer
NDE	Non-Destructive Examination
NEET-ASI	Nuclear Energy Enabling Technologies-Advanced Sensors and Instrumentation
PZT	Lead Zirconate Titanate
PWR	Pressurized Water Reactor
SETH	Separate Effects Test Holder
TREAT	Transient REActor Test Facility

Integration Testing of Ultrasonic Deformation Sensor for TREAT Experiments

1. Introduction

The TREAT facility was specifically designed to conduct transient reactor tests to simulate conditions ranging from mild upsets to severe reactor accidents. Transient irradiation of nuclear fuel samples is performed to identify fuel performance limitations. Of particular interest is testing conducted on pre-irradiated fuel samples to determine end-of-life performance limits that typically dominate fuel design. A significant challenge in these tests is the deployment of instrumentation for quantifying fuel condition (such as temperature, thermal conductivity, and mechanical condition) while minimizing any changes in these conditions due to the presence of the sensor itself.

A host of instrumentation was used during the operation of TREAT between 1959 and 1994 [1] to generate data necessary for fuel performance quantification. Much of the instrumentation capability from the previous TREAT operations will need to be resurrected, and a significant development, qualification, and integration effort may be necessary before some of these measurement technologies can be redeployed. The unique operating characteristics of TREAT (short bursts of high energy radiation) also challenge many sensors and instrumentation that may otherwise be deployed in-pile in test reactors. Ongoing research and development is addressing several instrumentation needs for TREAT experiments, with details of these advances documented elsewhere [1-3].

Among the key parameters of interest for monitoring during transient tests is the deformation of each component of the fuel pin. While linear variable differential transformer (LVDT) transducers are a potential solution, the sensitivity and response times of these sensors may be limited. The size of typical LVDTs and need for a push-rod connected to the sample make them intrusive and difficult to use in a constrained environment (such as the test capsules proposed for use in TREAT [3]). In addition, typical LVDT sensors are limited in their ability to provide data on radial deformation of the fuel pins.

An ultrasonic measurement approach could enable rapid, accurate measurements of deformation in axial and radial directions in fuel pins during TREAT irradiation tests. This is the focus of the work described in this report.

The overall objective of this work is to design an ultrasonic sensor capable of *rapid, non-contact, in-situ* measurements of dimensional changes in pre-irradiated fuel during re-irradiation. Specifically, the proposed sensor design will target:

- Reliable operation at elevated temperatures (between ~300ºC and 600ºC)
- Design compatibility with proposed near-term TREAT irradiation capsule concept designs [3]
- Direct measurement of fuel dimensional changes, including fuel rod diameter
- High-speed measurements to enable rapid characterization of changes during a transient test.

In addressing this research scope, we will leverage prior research in long-term piezoelectric sensor material survivability using in-pile sensor tests in materials test reactors (including previous NEET-ASI research) and in ultrasonic characterization of irradiated fuel specimens [4-7]. While irradiation (specifically, total dose) and time-at-temperature (especially above ~600˚C) are not expected to be a significant issue during TREAT transient tests, the ability to design the sensor to withstand such environments will increase sensor and measurement reliability. Prior research in compensation techniques [8], and advances in measurement science including higher bandwidth instrumentation, high-speed data acquisition devices and low noise electronics enable increased accuracy and precision from ultrasonic measurements. Recent results from post-irradiation examination of irradiated fuel using commercial-off-the-shelf ultrasonic probes and instrumentation [9] also demonstrated the potential sensitivity of ultrasonic measurements to fuel dimensions (and potentially to microstructure) and the ease with which commercial ultrasonic probes and instrumentation can be applied to irradiated fuel.

1.1 Objectives

The overall objective of this work is to design an ultrasonic sensor capable of rapid in situ measurements of dimensional changes in pre-irradiated fuel during re-irradiation. The objective of the research presented in this report was to identify and develop a prototypic sensor configuration for measuring fuel dimensional changes. The research utilized a set of static and dynamic laboratory-scale tests to evaluate potential sensor configurations and select a candidate configuration for further development and evaluation.

This report follows previous technical reports [10-14] that described the functional and operational requirements for an ultrasonic sensor for monitoring fuel dimensions during a transient test, identified materials for use in fabricating the sensors, identified potential sensor concepts for use in TREAT capsules, and described the initial design and evaluation of the sensor prototype.

This report details work, to date, toward development of the targeted non-contact, water coupled sensor configuration that is functional within the confines of a SETH capsule. This involved a "miniaturization" of the sensor design. The figure below shows a comparison of the size of the sensor used in the work for the previous deliverable next to a 3D-printed section of a SETH.

1.2 Report Organization

Section 2 of this report briefly discusses background information on ultrasonic measurements. Section 3 summarizes progress made to date. Section 4 details the current state of sensor design and testing. The report is summarized in Section 5.

2. Background

Ultrasonic measurements of deformation can provide nondestructive measurements of dimensional changes rapidly (within tens to hundreds of microseconds). Further, these methods are sensitive to both microstructural changes due to damage (from thermal, mechanical, and irradiation environments) and gross structural changes (such as swelling). As a result, ultrasonic methods have been applied to address needs in the nondestructive evaluation of structural components in nuclear power plants (including fuel cladding) during periodic pre-service and in-service inspection inspections.

Ultrasonic measurements have been successfully used for nondestructive materials characterization, including nondestructive evaluation (NDE) of degradation and damage [15], microstructure characterization [16], quantification and visualization of structural changes [17, 18] and process control [19]. Ultrasonic NDE is a critical element of the nuclear power industry's in-service inspection program for maintaining the integrity of the pressure boundary [20], and is being actively investigated for post-irradiation examination of fuels [21]. Ultrasonic measurements, typically performed at 10 MHz or higher [4], performed post irradiation show that fuel microstructural parameters, such as porosity and grain size, can be correlated to ultrasonic velocity [5,21].

Ultrasonic methods historically have seen limited applicability to environments with high temperatures and irradiation. Though some environmental factors (such as temperature) affect the measurement (sound speed, for instance), the limitation is primarily due to the probes themselves. Most commonly, lead-zirconate-titanate (PZT) is used as the piezoelectric sensor material for ultrasonic nondestructive measurements. PZT is limited in its applicability at elevated temperatures (approximately above 300ºC). However, recent tests (through DOE-NE's NEET-ASI program) have identified a number of alternatives that can operate at elevated temperatures (in excess of 400ºC) and can survive irradiation [6]. Certain grades of PZT have also been demonstrated for use in imaging under-sodium in sodium fast reactors [17]. A number of prior studies have also examined piezoelectric sensor material survivability using in-pile sensor tests in materials test reactors and in ultrasonic characterization of irradiated fuel specimens [4,5,8,21]. Recent advances in high-temperature ultrasonic sensor design has led to ultrasonic sensors that have demonstrated survivability at 550˚C for several weeks, under thermal cycling [22].

3. Summary of Prior Progress

3.1 Sensor Requirements

This report was used to document relevant information detailing the TREAT reactor, likely experiment capsules, and facilities have been included. Also, information on the required measurement speed and resolution and design constraints were documented through literature reviews and interactions with TREAT team leads. The SETH capsule was selected as a first target application, as it is planned for near term deployment, matches most of the design considerations of other planned capsules, and is designed to be used for sensor testing, along with fuel and material irradiations.

3.2 Materials Selection

This report considered piezoelectric magnetosrictive materials of interest. Materials considered included aluminum nitride, bismuth titanate, lithium tetraborate, lithium niobate, Remendur, and Galfenol. Other sensor types, such as EMAT sensors were also assessed. Piezoelectric sensors, with bismuth titanate and lithium niobate being used as the active elements, are considered the most promising with some focus also devoted to fabrication of AlN sensors.

3.3 Sensor Conceptual Design

The sensor conceptual design is based on previous work designing sensors for temperatures exceeding 550˚C [17]. Due to material survivability at these elevated temperatures, conventional bonding techniques are not applicable and a pressure-coupled approach is used, being careful of thermal expansion effects of the differing materials. This sensor design was used as a starting point for the design of a sensor to fit within the constraints of the SETH.

3.4 Mockup and Integration Planning

This report described progress on planning for integration of the sensor into TREAT experiments and on development of mock-up testing capabilities.

3.5 Initial Prototype Sensor Design and Evaluation

This report described potential prototype sensor design involving one or more pairs of transducer elements positioned 180° from one another with the tube being measured located between them. This design was shown to be sensitive to changes in tube diameter during expansion due to outward stresses and potentially to tube wall thickness at desired levels of accuracy. The tests described in this report demonstrated that the tube diameter values recorded by the measurements of the ultrasonic sensor design match measurements of DIC and calipers well.

4. Current Status of Sensor Design

The objective of the current deliverable is to continue the development of this arrangement toward a design that is functional within the confines of a SETH capsule. This involved a “miniaturization” of the sensor design. The figure below shows a comparison of the size of the sensor used in the work for the previous deliverable next to a 3D-printed section of a SETH.

Figure 1. Printed SETH mock-up with conceptual sensor based on prior development.

The miniaturization involves decreasing both the sensor diameter and the sensor depth. From a perspective of simply ensuring that the sensor fits inside the space within the SETH surrounding the central rod being measured, the sensor depth is the most important dimension. However, the diameter is also of concern as the convergence point of the wave from the transducer is a function of the piezoelectric crystal diameter. So miniaturization of the sensor diameter is also desired.

In addition to reducing the dimensions of the sensors to fit within the SETH, consideration was given to the piezoelectric crystal material used for the sensor to be used in the integrated test. The results presented in the previous milestone report were generated from tests performed with PZT, which does not perform well at high temperatures. Instead, bismuth titanate (BiT) and aluminum nitride (AlN) are preferred materials.

The approach that we chose to take in moving toward integrated tests was to make single design parameter changes incrementally in order to track the effects of the changes to be able to eventually tune parameters for generating an optimal sensor. This approach was to first change the sensor material to compare to the results generated in the previous milestone report, second to adjust the depth of the sensor, and third to reduce the diameter of the sensor. This way, if unexpected behavior were to manifest, we would be able to assign it to the proper cause and make appropriate adjustments.

Recognizing that measurements at temperature would need BiT or AlN, the first step in the modification of sensor design toward integrated testing was to make comparative measurements to PZT with these materials. As AlN is less accessible, we proceeded with measurements with BiT. At the same time, we pursued fabrication of AlN sensors with the small inventory of AlN in our possession. Measurements were made with different surface polishes as well as with thinner backing on a stainless steel test block, with the results shown in Figure 2 below. The first 2 waveforms are generated with BiT piezoelectric crystals in which the bottom face had been polished smooth, removing the electrode. The third and fourth waveforms are generated with standard BiT piezoelectric crystals with both electrodes intact. The fifth waveform is a pressure coupling arrangement with a thinner backing using the standard, unpolished piezoelectric crystal. The results show that the polishing of the surface does not greatly affect the performance of the sensor, yet the thinning of the backing material does create some deviations from optimal performance. This was taken into account moving forward with the sensor design.

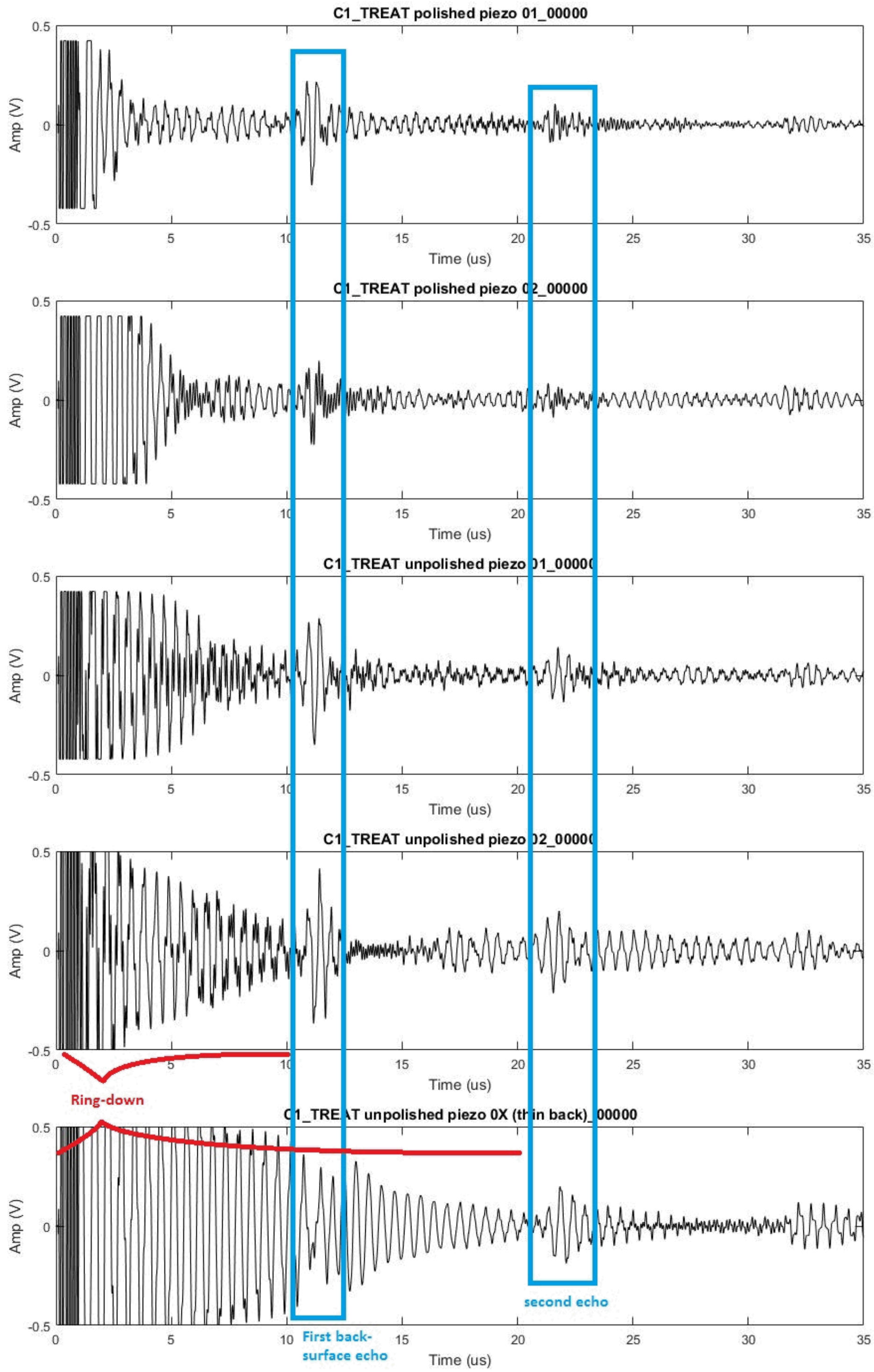

Figure 2. Effects of polishing piezoelectric element on signal.

4.1 TRANSDUCER DESIGN AND TESTING

Based on available piezoelectric crystals to develop a preliminary sensor to test in a high-temperature environment, BiT and AlN were selected. Both piezoelectric crystals materials were 1 mm in thickness, which results in a center frequency of 2.0 MHz. The shift down in frequency from the 15 MHz tests performed on the benchtop tube straining tests previously [14] is expected to have a minimal impact on measurements of the tube surface. Signal resolution is mostly governed by the sampling rate of the data acquisition system over the frequency of the transducer. To test this, a standard PZT immersion transducer at 2.0 MHz was selected to verify the resolution using a lower frequency.

Figure 3. 2.0 MHz transducer being translated perpendicular to a plate reflector

A test plate was held stationary while the 2.0 MHz transducer was translated with an encoded scanner along its axis away from a plate reflector as shown in Figure 3. Waveforms were collected at 1 um increments over a range of 2 to 4 mm distance from the tube. These collected waveforms were then analyzed to identify the measured signal time versus encoded scanner position. Figure 4 shows the overall result, with a zoomed-in section shown in Figure 5.

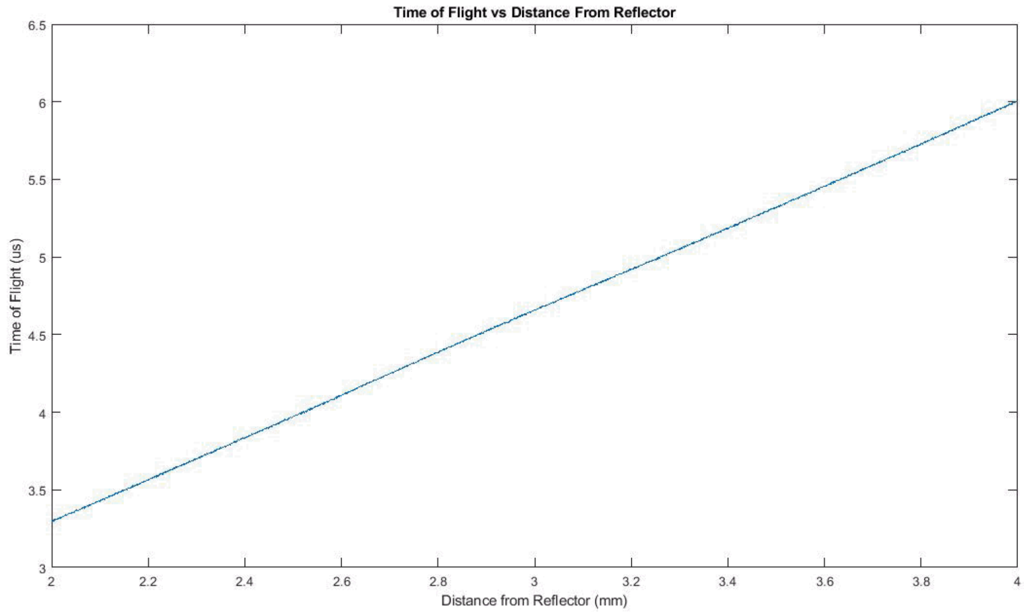

Figure 4. Time of flight vs stand-off distance for 2.0 MHz transducer response off plate reflector.

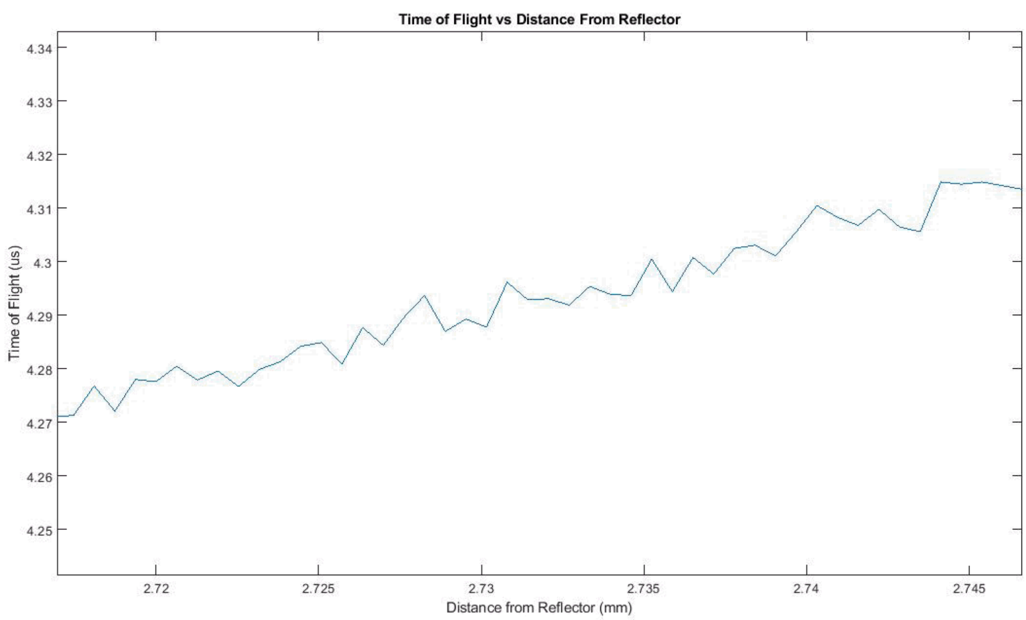

Figure 5. Zoomed in region of Figure 4.

The data in Figure 3 shows that the overall trend is still linear for a 2.0 MHz transducer and, while there is variability seen in when looking at a zoomed-in region of the data, the level of noise is likely contributed to the uncertainty in position of the transducer caused by using a scanner while trying to make highly precise measurements. This effect should be reduced when using a transducer with a fixed position and measuring sample displacement.

4.2 AlN Evaluation

Due to the higher temperature survivability of AlN over BiT, piezoelectric crystals should be attached directly to the transducer housing via brazing. This results in more consistent contact and reduces the overall height of the sensor, removing components required for pressure-coupling. Two AlN piezoelectric crystals, each with a nickel cup, were sent off to be brazed externally and then sent back to PNNL for evaluation of the bond. Figure 6 shows the received components.

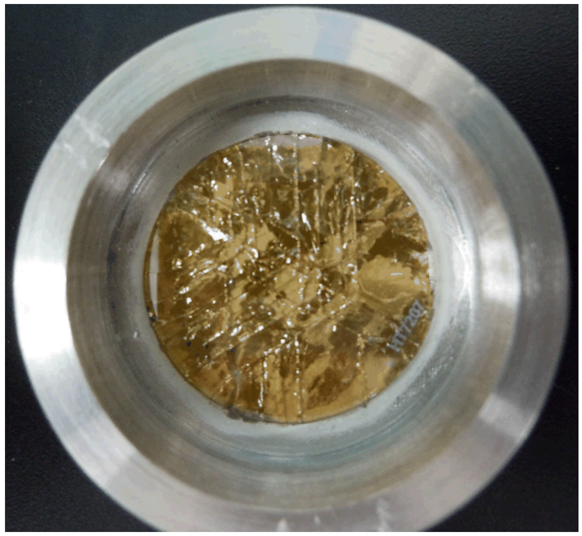

Figure 6. Initial attempt to braze AlN crystal to nickel transducer face.

It was determined that the nickel cup deflected under heating, shattering the crystal. The dark-areas in image show bonded regions. This bonding was verified through acoustic microscopy. The transducer was tested to evaluate whether it could still be used, but no detectable echo signals were identified (echo expected at ~21 μs in Figure 7).

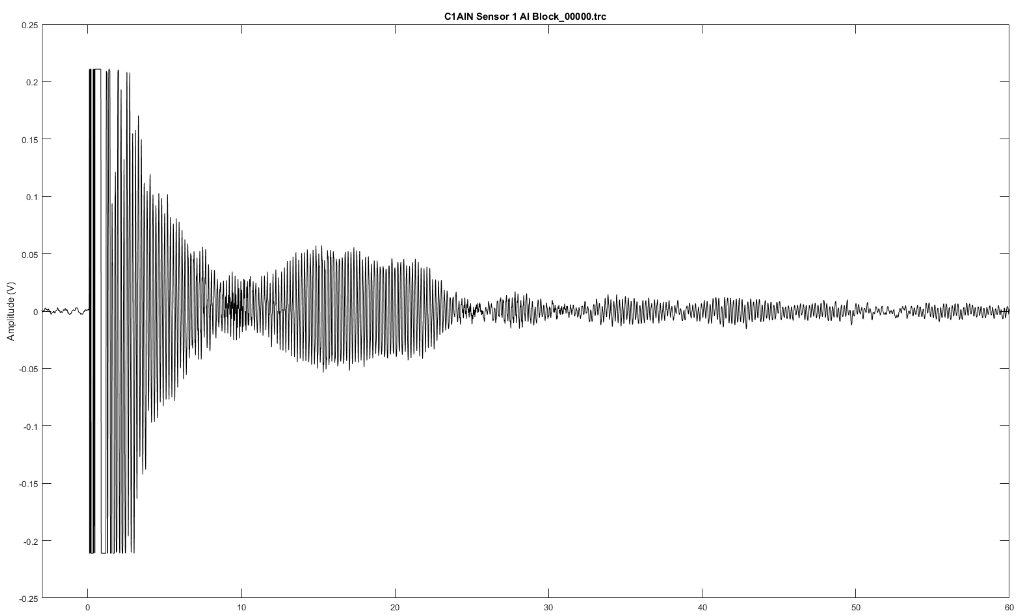

Figure 7. Signal from brazed AlN transducer.

4.3 BiT Probe Design

Using the constraints of the inner diameter of the SETH, the sensor to be used in testing had to be able to remain pressure coupled with backing, while still fitting within the vessel, providing enough standoff between the face of the transducer and the surface of the central tube. Leveraging previous high-temperature sensor design work, a test design was created to fit these specific space constraints. Figure 8 shows the sensor design assembly and demonstrates its expected fit within the SETH based on design dimensions.

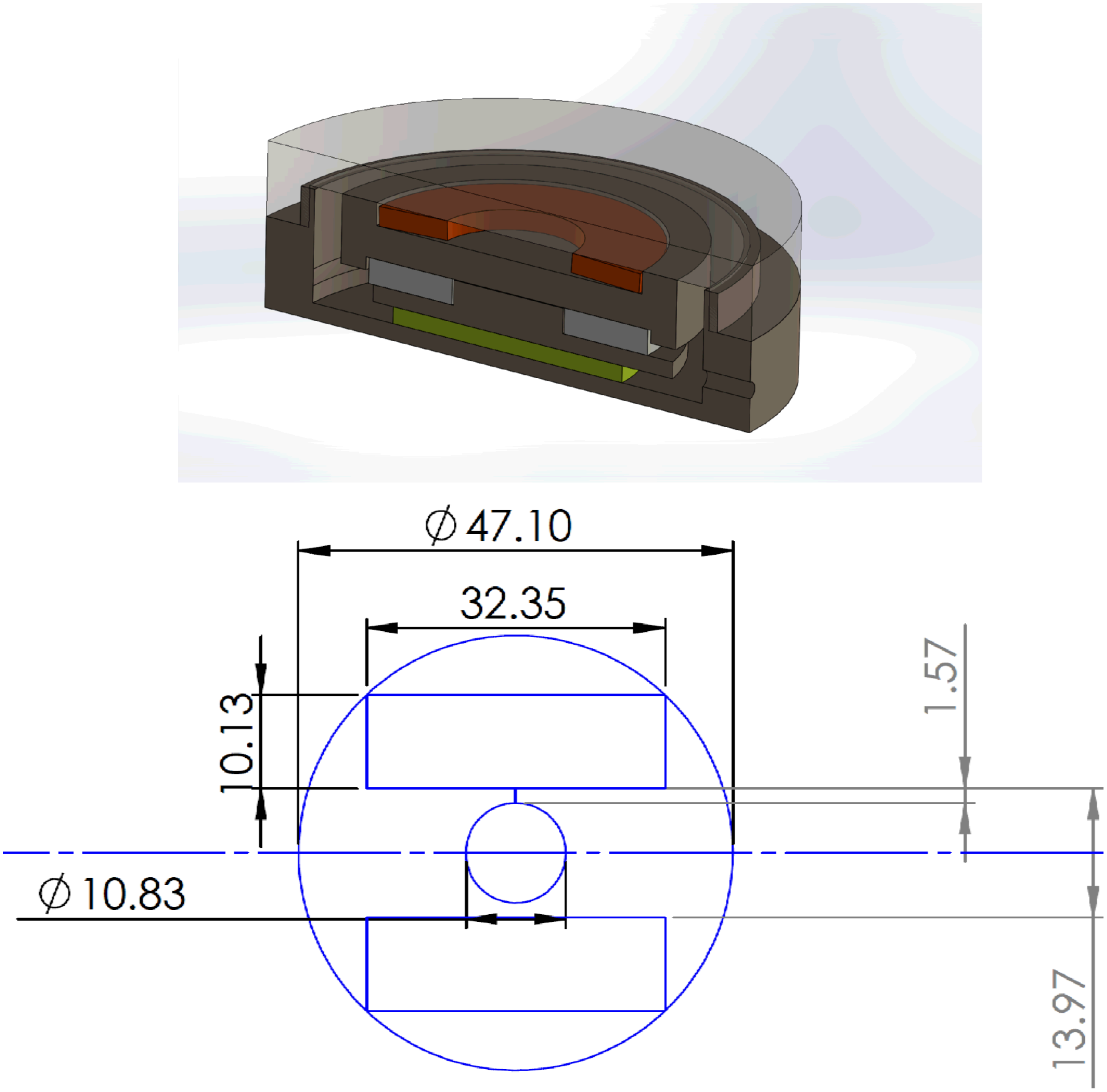

Figure 8. Cutaway CAD drawing of sensor prototypic design and dimensioned plan view.

Based on the final design, two test-sensors were fabricated to evaluate the signal quality and functionality of the transducer with a response off a surface parallel to the probe face. Both sensors were immersed in water opposite a plate reflector, and the distance between the two was varied by moving the plate. The setup employing a similar configuration to that used in the preliminary 2.0 MHz testing shown in Figure 3.

No response was detected off of the plate reflector from either of the two test-sensors that were constructed. Further analysis was done to identify potential issues resolving a signal response in the existing configuration. After disassembly of the transducer, components were tested both by themselves and as partial assemblies on a stainless steel test block. Figure 9 shows different waveforms during diagnostic testing of the sensor configuration

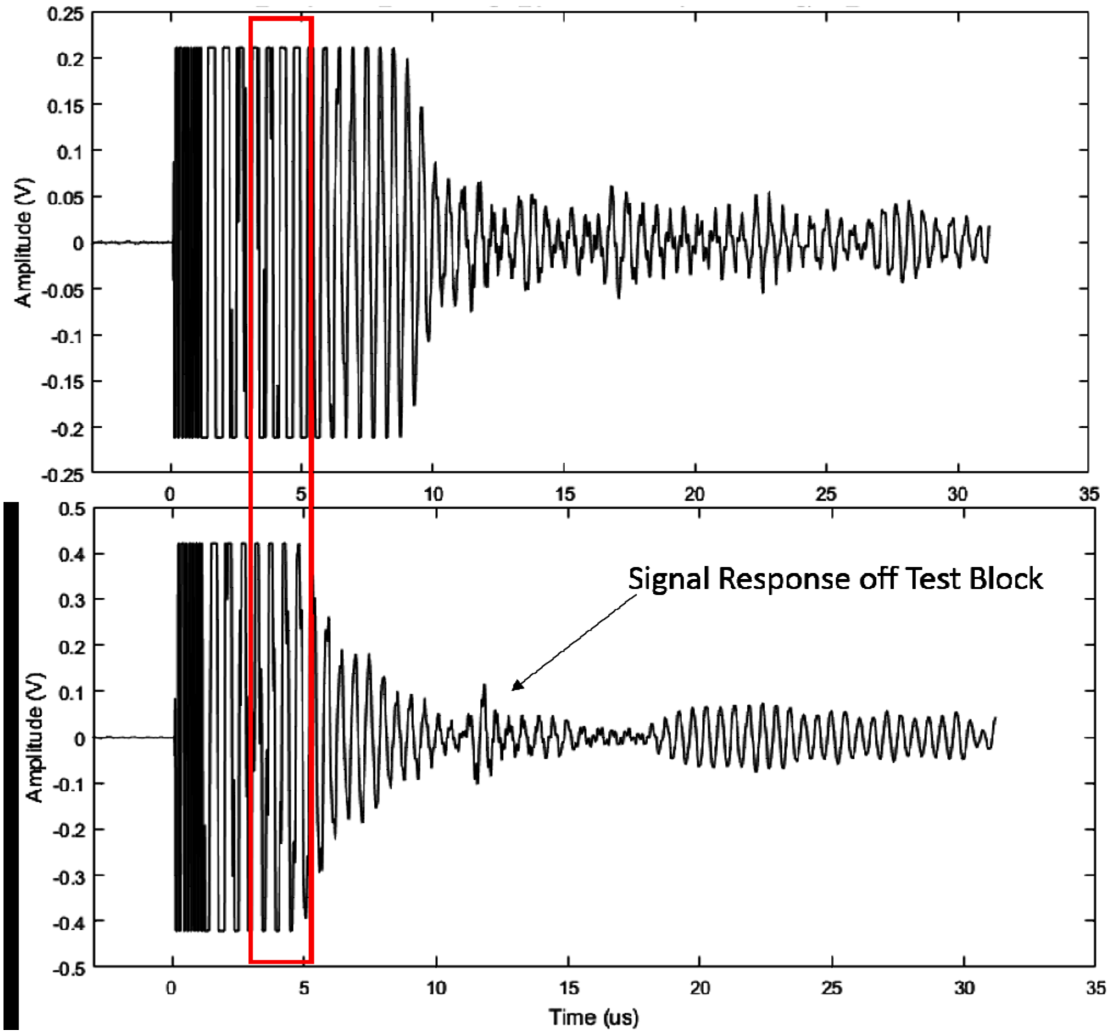

Figure 9. Signal response with the designed pressure (top) and additional loading (bottom)

Based on the diagnostic testing, it was determined that the limiting factor appeared to be insufficient pressure to couple the piezoelectric element to the transducer face as the primary failure. However, even with additional loading on the back of the test sensor, the expected signal response within the SETH is expected to be around 5 us (highlighted in the red box in Figure 9) based on the distance between the sensor and the tube. This will be lost in the underdamped ringing of the piezoelectric element from excitation. The test-probes designed were not meant to operate within the SETH, but simply to provide a design basis for a sensor that would physically fit within the SETH due to space constraints. The reason for this is the BiT material available were too large to operate at such short distances. Transducers are designed to be operated in the far-field, past the convergence point of the beam. This equation is:

(1)

Where d is the distance away from the sensor to the start of the far-field, D is the diameter of the piezoelectric crystal, f the center frequency, and v the velocity of the medium the sound is moving through. Due to the large size of the piezoelectric crystals that were available for the preliminary design and testing, 15mm diameter, the convergence point for these transducers in water is 57 mm. To adjust this focal point to match the designed stand-off within the SETH of 1.57 mm shown in Figure 8, d was held constant. Since the velocity doesn't change significantly during testing, the parameters that need to be altered are either the center frequency or diameter of the piezoelectric crystal. Table 1 shows the diameters with respect to different frequencies, while maintaining a convergence of 1.57 mm.

Table 1. Required piezoelectric element diameter for desired stand-off distance at specific frequencies.

f (MHz)	1.0	1.5	2.0	5.0	10.0
D (mm)	3.05	2.49	2.16	1.36	0.97

If the frequency is held at 2.0 MHz, the diameter of the piezoelectric crystal needs to be no greater than 2.16 mm. Due to the expected expansion of the tube, the target diameter for future sensors will be 2 mm. This reduction in sensor diameter will also reduce the overall size of the housing, which will slightly increase the standoff within the SETH.

4.4 Near Term Testing Options

The next stage of testing will be in semi-prototypic environments; elevated temperature aqueous environments. Several options will be considered depending on availability, data needs, and sensor design constraints.

The first option is autoclave testing. Autoclaves at INL were designed to mimic steady-state PWR temperature and pressure, with maximum levels of 2500 PSI and 325 °C. The autoclaves have inner diameter of 127 mm and sufficient length to accommodate either a free hanging sensor and fuel rod simulant or a SETH capsule containing the sensor and fuel simulant.

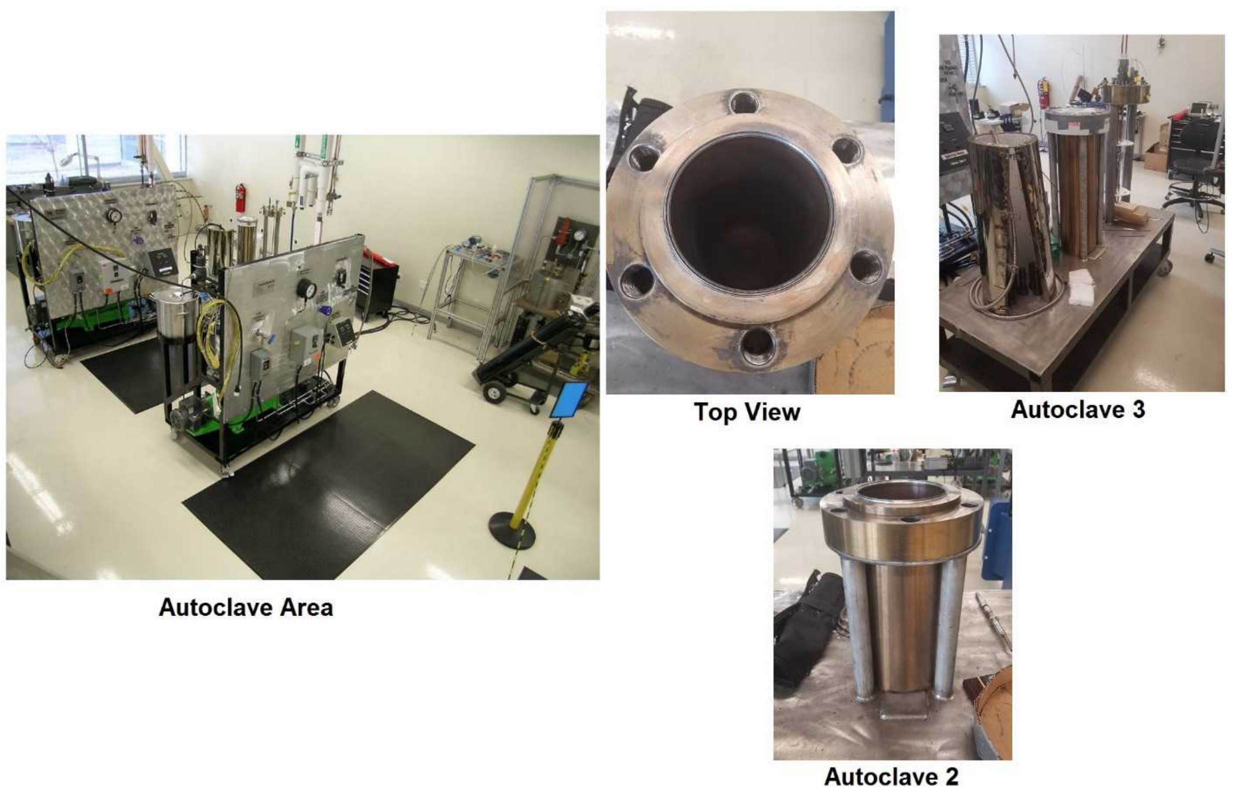

Figure 10. INL autoclaves.

The second option is a water filled SETH capsule heated with a cartridge heater. Previously, this setup (shown in Figure 9) was used with a gas fill to reach 800 °C for testing temperature sensors. Some modifications will be necessary to operate the cartridge heater under water filled conditions and, without the ability to operate under pressure, temperatures would be limited to natural boiling temperature at local atmospheric pressure.

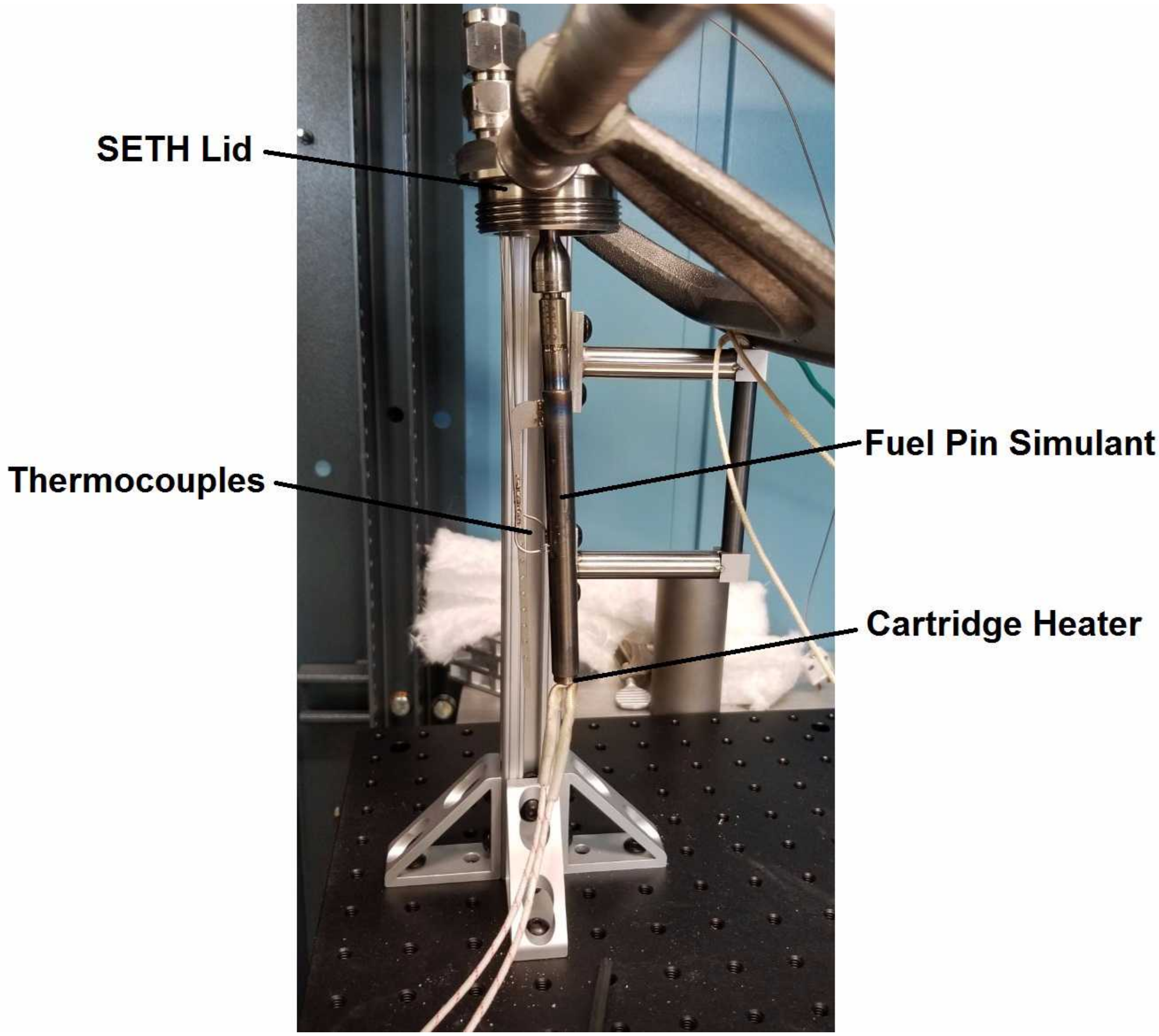

Figure 11. Cartridge heater installed within SETH capsule.

Last is a test fixture under development for mimicking the rapid boiling which occurs under TREAT transients. This test fixture utilizes a capacitor bank to rapidly heat a test section, within an autoclave, through Joule heating, approximating the heat rates provided by TREAT transient irradiations. This capability is still developmental and, as of this report, has not been tested. If successful, this would be an ideal facility for testing the ultrasonic deformation sensor.

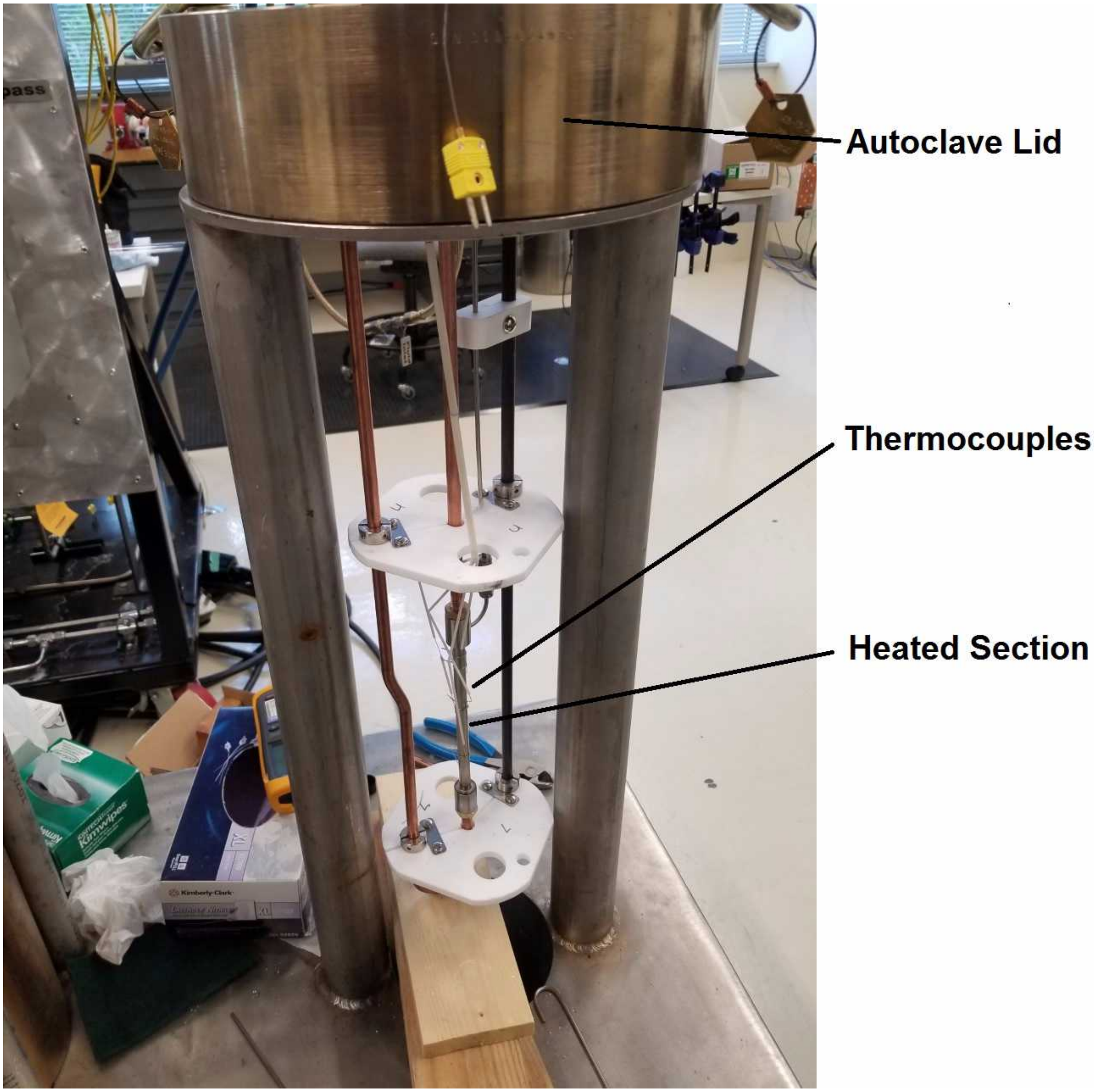

Figure 12. Transient boiling autoclave fixture.

5. Conclusions

This report documents efforts to refine, fabricate, and test the sensor design presented previously [14] with the requirement that it fit within the confines of a SETH capsule. This design utilizes materials that will survive at higher temperatures. Functionality requirements led to the desire to develop brazed or pressure-coupled designs to eliminate the use of coupling materials that may not function well at higher temperatures. Brazing attempts with AlN failed due to deflection of the nickel cup during brazing. Future attempts will use a thicker cup that will be mechanically thinned after brazing to prevent this phenomenon. Pressure coupling attempts with BiT were also unsuccessful as it was determined that much more pressure was necessary that anticipated to generate signals of desired quality. In order to address this result, future designs will use a high temperature conductive coupling material in place of a pressure coupling design. This coupling of a BiT element to backing material with a high temperature, electrically conductive coupling material is currently being pursued. After demonstration of functionality, testing within the autoclaves as discussed in the previous section will commence.

6. References

1. C. Jensen, et. al., "FY17 Report for Instrumentation Development for the Transient Testing Program," INL/EXT-17-43444, Sept., 2017.
2. Colby Jensen, "Experiment Instrumentation for Transient Testing," Advanced Sensors and Instrumentation 2016 NE I&C Review, Oct. 12-13, 2016
3. C. Jensen, "Transient testing instrumentation needs," Presented at the *2016 DOE-NE ASI Program Review*, October 2016.
4. D. Fourmentel, J. F. Villard, et al, "Acoustic sensor for in-pile fuel rod fission gas release measurement," in *First Int'l. Conf. on ANIMMA*, 2009, pp. 1-5.
5. K. K. Phani, D. Sanyal, and A. K. Sengupta, "Estimation of elastic properties of nuclear fuel material using longitudinal ultrasonic velocity – A new approach," *J. Nucl. Mater.,* vol. 366, pp. 129-136, 6/30/ 2007.
6. J. Daw, J. Rempe, *et al.*, *NEET In-Pile Ultrasonic Sensor Enablement-Final Report*, Technical Report, PNNL-23746 (INL/EXT-14-32505), 2014.
7. P. N. Bilgunde and L.J. Bond, "Effect of Thermal Degradation on High Temperature Ultrasonic Transducer Performance in Small Modular Reactors," *Physics Procedia* 70:433-436, 2015.
8. R. Jacobs, P. Ramuhalli, and A. Casella, "Characterization of microstructural differences in irradiated nuclear fuel using ultrasonic NDE," *IEEE Trans. UFFC* (In preparation).
9. Ramuhalli P, R Jacob, P MacFarlan and A Casella. 2017. "Microstructural Characterization of Irradiated U0.17ZrH1.6 Using Ultrasonic Techniques." Trans. ANS 116(361-364).
10. J. Daw, A. Crawford, R. Skifton, L. Hone, P. Ramuhalli, R.E. Jacob, A.M. Casella, R.O. Montgomery, "Design Requirements for Ultrasonic Deformation Sensor for TREAT Experiments," INL/EXT-18-45209, 2018.
11. P. Ramuhalli, R.E. Jacob, R.O. Montgomery, M. Prowant, M.S. Good, J. Daw, "Preliminary Sensor Design Concepts for Ultrasonic Dimensional Measurements," PNNL-28092, 2018.
12. P. Ramuhalli, M.S. Good, R.E. Jacob and J. Daw, "Preliminary Assessment of Sensor Materials for TREAT Ultrasonic Dimension Sensor," PNNL-27727, 2018.
13. J. Daw, A. Crawford, R. Skifton, L. Hone, A.M. Casella, M. Prowant, M. Good, C. Hutchinson, T. Roosendaal, R. Montgomery, "Status of Mockup and Integration for Ultrasonic Deformation Sensor for TREAT Experiments," INL/EXT-19-53110, 2019.
14. A.M. Casella, M.S. Good, T. Roosendaal, C. Hutchinson, R. Seffens, M. Prowant, R.O. Montgomery, F. Luzi, P. Ramuhalli, J. Daw, "Complete Initial Ultrasonic Sensor Prototype Design and Preliminary Evaluation," PNNL-28753, 2019.
15. D. Ensminger and L. J. Bond, *Ultrasonics: Fundamentals, Technologies, and Applications*, 3rd ed.: CRC Press, 2012.
16. P. Ramuhalli, R. V. Harris, *et al.*, "In-situ Characterization of Cast Stainless Steel (CASS) Microstructures," ed. Berlin, Germany, 2010.
17. M. R. Larche et al, "Progress in the development and demonstration of a 2D-matrix phased array ultrasonic probe for under-sodium viewing," *AIP Conf. Proc.*, Vol. 1706, Issue 1, 2016.
18. D. R. Weier, and A. F. Pardini, *Evaluation of UT Wall Thickness Measurements and Measurement Methodology*, Technical Report, Pacific Northwest National Laboratory, PNNL-16828, Oct 2007.
19. L. C. Lynnworth, *Ultrasonic Measurements for Process Control: Theory, Techniques, Applications*: Elsevier Science, 2013.
20. S. R. Doctor, "Nuclear Power Plant NDE Challenges - Past, Present, and Future," presented at the *Review of Progress in Quantitative Nondestructive Evaluation*, Portland, Oregon, 2007.
21. D. Baron, D. Laux, and G. Despaux, "Mechanical characterisation of irradiated fuel materials with local ultrasonic methods," in *Pellet-clad Interaction in Water Reactor Fuels*, 2004.

22. Prowant M, G Dib, H Qiao, M Good, M Larche, S Sexton and P Ramuhalli. 2017. "Preliminary Design of High Temperature Ultrasonic Transducers for Liquid Sodium Environments." In Review of Progress in Quantitative Nondestructive Evaluation, Provo, UT.
23. "FUTURE Transient Testing of Advanced Fuels," Summary of the May 4-5, 2009 Transient Testing Workshop Held at Idaho National Laboratory, 2009.
24. "TREAT Baseline Description Document," ANL/RAS 72-23, Aug., 1972.
25. N. Woolstenhulme, C. Baker, J. Bess, D. Chapman, C. Jensen, C. Hill, D. Wachs, S. Wilson, "Status Report for NEET In-Pile Sensor Irradiation Capabilities at TREAT," INL/EXT-17-43274, Sept., 2017
26. N.E. Woolstenhulme, "Update on TREAT Restart and Experimental Design Preparations," OSU IRP Meeting November 2017, Corvallis, WA.
27. Dan Wachs, "Status of Transient Testing Capabilities in the United States," GAIN Workshop on Fuel Safety Research, Idaho Falls, ID, May1-5, 2017.
28. D. Sunderland, et. al., "Evaluation of Recent RIA-Simulation Experiments with the FALCON Fuel Performance Code," Proceedings of the 2004 International Meeting on LWR Fuel Performance, Orlando, FL, 2004.
29. Bauer et al., BEHAVIOR OF METALLIC FUEL IN TREAT TESTS, Nuclear Technology, Vol. 92, 1990.