Transactions, SMiRT-25
Charlotte, NC, USA, August 4-9, 2019
Division VIII

ADVANCED NDE TECHNOLOGIES FOR DETECTING AND MANAGING AGING AND DEGRADATION IN REACTOR COMPONENTS

P. Ramuhalli[1], M. Prowant[2], H. Qiao[2], M. Good[2], C. H. Henager Jr.[2]

[1] Distinguished R&D Staff Member, Oak Ridge National Laboratory, Oak Ridge, TN, USA (ramuhallip@ornl.gov)
[2] Senior Research Scientist, Pacific Northwest National Laboratory, Richland, WA, USA

ABSTRACT

Recent research in nuclear power reactors has focused on the development and deployment of technologies for improving the economics of nuclear power plant (NPP) operation. Of interest, both from an economic and safety perspective, is the management and mitigation of aging-related degradation in critical components. In this paper, we describe potential techniques for nondestructive evaluation (NDE) that may be adapted for online monitoring of component aging in advanced non-light water reactors (ANLWR). The implications of the operating environment on the NDE measurement, especially when conducted continuously with the sensor placed in situ, are described. The design of sensors that can be used for monitoring component aging in situ and online are discussed, and results from laboratory testing at elevated temperature are outlined. Laboratory testing indicates the sensor can survive the operating temperatures in ANLWRs while providing a reasonable measurement signal-to-noise ratio. Ongoing research is focused on further testing and refining the sensor design and measurement procedures for deployment in ANLWR environments.

INTRODUCTION

The U.S. fleet of commercial nuclear power reactors has an average age of more than 30 years, and most of the fleet has either applied for or received an extension of the operating license from 40 years to 60 years. In 2018, plants began applying for subsequent license renewal for extending operation from 60 years to 80 years. In addition, there is interest in the design and deployment of advanced reactor concepts, including small modular reactors and advanced non-light-water cooled reactor (ANLWR) concepts. In all instances, it is looking increasingly likely that the primary challenge to long term operation of these reactor concepts will be economic and will require the development and deployment of technologies for improving the economics of nuclear power plant (NPP) operation.

A challenge to economic long-term operations is the life-limiting nature of materials aging and degradation, as such aging and associated degradation in the structural response of the material can limit operating margins. Replacement of a subset of components (such as the steam generator) may be possible,

---

Notice: This manuscript has been authored by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE). The US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

though the costs associated with the replacement of larger components (including the cost of time offline) may be prohibitive. Thus, management and mitigation of aging-related degradation in critical components becomes important to maintaining safety margins and optimal operations.

Current in-service inspection (ISI) practices for LWRs are based on requirements in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC), which were originally developed for the management of fatigue degradation (Doctor 2008). Methods (such as ultrasonics and eddy current nondestructive evaluation [NDE]) for detecting material degradation in LWRs have been shown to be reliable for detecting cracks or significant areas of corrosion in materials currently used in NPP construction (Bond, Doctor et al. (2008) (Bond 1988). However, approaches to mitigating the growth of large cracks are limited; and for sustainable long-term operations, the need is to detect and assess degradation before the onset of large-scale cracking to enable proactive mitigation and control of degradation growth. The use of online monitoring technologies for monitoring component aging can enable timely decision-making that is risk-informed (Ramuhalli, Coble et al. 2013). Adapting these concepts to monitoring and managing materials aging and degradation will require advanced NDE methods that are sensitive to early stages of degradation (Meyer, Ramuhalli et al. 2013), NDE sensors that can provide drift-free, long-term operation at higher temperatures (Korsah, Kisner et al. 2016), and algorithms for analysis of the resulting data.

More recently, ASME Code requirements have been expanded to address diverse and challenging degradation mechanisms in nuclear power plants, such as stress corrosion cracking (SCC), and are being expanded to address ANLWRs. For the most part, ASME Code recommendations for inspection of ANLWR safety-critical components appear to be focused on basic, mostly visual examination, techniques and condition monitoring (CM) using leak detection (Chang, Grandy et al. 2005).

It is likely that traditional volumetric (ultrasonic) and surface (eddy current and visual) ISI methods can detect and characterize cracking in ANLWRs. However, challenges in translating these methods to ANLWRs include:

- Limited ability to perform ISI due to the physical properties of the coolant. For example, optically opaque coolants such as liquid metal coolants being considered for advanced reactors (Diaz, Chamberlin et al. 2016) can limit the applicability of visual techniques. Similarly, liquid metal coolant electrical conductivity may limit the ability to perform in-vessel eddy current inspections.
- Limited access to many of the components of concern (such as the intermediate heat exchanger and primary pump tanks) being submerged in liquid coolant. ISI of primary system components may require draining the coolant to provide access and require high-temperature-and-radiation-tolerant sensors that can locate the component and perform the inspection.

Ongoing research at the US Department of Energy National Laboratories is addressing these challenges. The focus of research is on identifying key indicators so that sensing methodologies may be developed for detecting and characterizing degradation early in its lifecycle. The goal is to develop sufficient information to enable prediction of remaining life, which in turn may be used to optimize inspection and maintenance scheduling. The paper describes ongoing research and discusses results to date.

NDE TECHNIQUES FOR EARLY DEGRADATION DETECTION

A number of NDE measurements are applicable to detect cracking (Raj, Moorthy et al. 2003). These include potential drop measurements, digital image correlation, x-ray diffraction, small-angle neutron scattering, acoustic birefringence, acoustic backscatter, nonlinear ultrasonics, etc. Each of these approaches is sensitive to different aspects of material microstructural changes, although the level of sensitivity varies by technique. Many of these methods are either unsuitable for online monitoring or require additional development for field deployment. A more detailed discussion of these and other techniques is provided in the literature (McCloy, Montgomery et al. 2013, Ramuhalli, Hirt et al. 2016). Of these techniques, the focus of the research described in this study is on ultrasonic methods for NDE.

Ultrasonic Methods for NDE of Nuclear Passive Components

While a number of measurement options exist for passive component inspection and monitoring (Meyer, Coble et al. 2013, Ramuhalli, Roy et al. 2014), the expectation is that a large fraction of NDE or online condition monitoring techniques in ANLWRs will be based on ultrasound. The reasoning behind this expectation is the widespread use of ultrasonic techniques for volumetric inspections of Class-1 components in the LWR fleet and the sensitivity of ultrasound to both cracking and microstructural parameters (for instance, Doctor, Bruemmer et al. 1989, Krautkrämer and Krautkrämer 1990, Goebbels 1994, Raj, Kumar et al. 2000, Ensminger and Bond 2011). We expect that ultrasound will be among the techniques that are deployed for in-vessel and primary system inspection and monitoring while one or more of ultrasonic, magnetic, electromagnetic, and visual methods may be used elsewhere at key locations (weld and base metal) that are considered to be at high risk of failure.

The advantage of ultrasonic techniques (bulk wave and guided wave) is their ability to monitor large regions of the structure volumetrically, potentially reducing the number of sensors needed for inspection and monitoring. Ultrasonic bulk-wave based NDE techniques have been applied for the inspection of Class 1 components in LWRs (Doctor 2008), while guided wave ultrasonics have been proposed for the inspection of piping (especially buried piping) (Meyer, Ramuhalli et al. 2013). Measurements of linear ultrasound parameters such as amplitude, velocity, and attenuation have been shown to correlate with microstructural changes common to thermal and mechanical aging in some metals (Raj, Mukhopadhyay et al. 2006). Variations, such as nonlinear ultrasonics (Cantrell and Yost 2001, Bermes, Kim et al. 2008, Shui, Kim et al. 2008), have been shown to be sensitive to early stages of degradation and cracking, although interpretation of the data can be challenging. Recent research has also indicated sensitivity of the nonlinear parameter to thermal aging (Matlack, Bradley et al. 2015, Li, Hu et al. 2019) and irradiation damage (Matlack, Wall et al. 2012).

A potential advantage of using ultrasonic sensors is their sensitivity to other parameters, such as temperature and fluid flow. These sensors may also be used in a passive (listen-only) mode for detecting acoustic emission (AE) from crack initiation and growth (Bentley 1981, Runow 1985, Jax and Ruthrof 1989, Hutton, Friesel et al. 1993), vibration monitoring, void formation in the coolant, and coolant flow.

Challenges

While ultrasound is a potential candidate for NDE in ANLWRs as well as other measurements of process and component condition, there remain challenges to the development and deployment of measurement techniques. The primary issue that appears to limit the possibility of using ultrasound in these reactors is the limited lifetime of conventional transducers (sensors). For instance, sodium-cooled fast reactors are expected to reach core outlet temperatures in excess of 500°C during steady state operation, while the temperature on the cold leg may exceed 400°C. An intermediate heat exchanger (IHX), submerged in liquid sodium, is expected to be used in pool-type reactors for heat transfer from the primary loop. In molten salt reactors, the temperature and neutron irradiation dose rates are expected to be higher. Sensors located on these components may be needed to quantify the presence and extent of any degradation given that the components will experience these severe conditions during operation.

The use of ultrasonic sensors for online CM in harsh environments typical of ANLWRs is likely to result in a gradual change in the sensor response and sensitivity because of sensor aging and degradation, especially in regions of high temperatures and irradiation (neutron and gamma) (Daw, Rempe et al. 2012). While recent advances (Tipireddy, Lerchen et al. 2017) may be used to monitor and compensate for sensor drift, improved sensor materials and sensor designs may be needed to maintain the ability to monitor the materials/components over the long term. Note that the need for improvements in ultrasonic sensor design exists even if their predominant use is for periodic inspections.

Previous research (documented in Ramuhalli, Dib et al. 2017) indicated that there were three potential options for ultrasonic sensor design, for the purposes of nondestructive inspection and monitoring of structural components in ANLWRs. These included a bonded transducer using adhesives, a pressure-coupled transducer concept (Prowant, Dib et al. 2018), and a direct bonding approach that deposited the piezoelectric material directly onto the structure without the use of adhesives. These studies identified the following improvements as necessary:

- Sensor material selection to increase sensitivity.
- Transducer construction material selection to increase sensitivity, robustness, reliability, and ease of fabrication.
- Transducer design optimization. This was specific to the pressure-coupled design concept with improvements identified as necessary in the overall pressure-coupling design to maintain consistent pressure during extended operation at temperatures in excess of 500°C and thermal cycling.

METHODS AND MATERIALS

To address the sensor compatibility issues for ultrasonic sensors, the research took a multi-pronged approach. We leveraged a number of advances from previous research, including selecting temperature and radiation-tolerant sensor materials (Daw, Palmer et al. 2015), sol-gel technology for field-fabrication of probes (Searfass, Tittmann et al. 2009), and high-temperature ultrasonic probes for under-sodium viewing (Bilgunde and Bond 2015, Diaz, Chamberlin et al. 2016). In order to focus efforts, the operational environment targeted for the initial design and evaluation was a notional sodium fast reactor concept, with a core outlet temperature of 500°C during operation and 270°C during hot standby. The assumption was that the ultrasonic transducer may be submerged in liquid sodium and used for long-term monitoring of the component condition. The improvements in the sensor design, along with results of long-term testing, are described below.

Sensor Material Selection

Sensor material selection was constrained by the high-temperature environment of 550°C (1022°F). Piezoelectric elements such as bismuth-titanate (BiT) and aluminium-nitride (AlN) have been identified as potential materials that will meet both sensitivity requirements of the signal as well as survivability in the high-temperature environment over extended operating times (Daw, Palmer et al. 2015). The current (initial) design uses BiT as the sensing element, which is mechanically coupled within the housing.

Transducer Material Selection and Sensor Design

Due to the mechanical coupling of the piezoelectric element to the probe, thermal expansion plays a large factor in design. Materials were selected that survive at higher temperatures and have similar thermal properties to avoid expansion inconsistencies throughout the probe when cycling the temperature down to 270°C (518°F).

Gold electrodes were sputtered onto each face of the BiT piezoelectric element for improved coupling. For the target of liquid sodium reactors, the sensor housing was constructed from nickel-200, which has shown the ability to wet over repeated trials in 270°C (518°F) liquid sodium (Diaz, Chamberlin et al. 2016). Glass solder was used to assist in the continuous coupling of the piezo to the face in this round of testing, in order to increase constant coupling between the piezo and faceplate of the sensor during these thermal cycling regions.

Fabrication and Testing

The sensors being tested were assembled in stages, with the glass solder used to attach the sensor face to a block for signal monitoring and testing as well as bonding the piezoelectric element to the faceplate of the sensor. The backing and mechanical loading elements of the sensor were then attached to the base cup, at which point the seams around the sensor can be welded to completely seal the sensor. For disassembly and diagnostic purposes of the probe after tests, the assembly was not welded.

Figure 1. Full sensor housing assembled with attached signal wires, on benchtop (left) and connected in furnace (right)

Once assembled, the signal wires were attached to the sensor, the sensor placed in a convection flowing air furnace (Figure 1), and the signal wires connected to measurement equipment for in-situ monitoring of the sensor as it was subjected to heating and thermal cycling for extended periods of time. Temperature was monitored and recorded with an external thermocouple while waveform measurements were collected every 20 minutes for the duration of the sensor testing, including initial heating and final cooling.

RESULTS

The results of the most recent sensor testing showed long-term survivability, with the sensor operating for 750 hours before the test was concluded. During that time, the temperature was cycled multiple times. Each thermal cycle lasted eight hours, with the temperature lowered from 550ºC (1022ºF) to 270ºC (518ºF) before resuming operating temperature (550ºC). The temperature profile of the testing, along with the signal amplitude during the test, is shown in Figure 2.

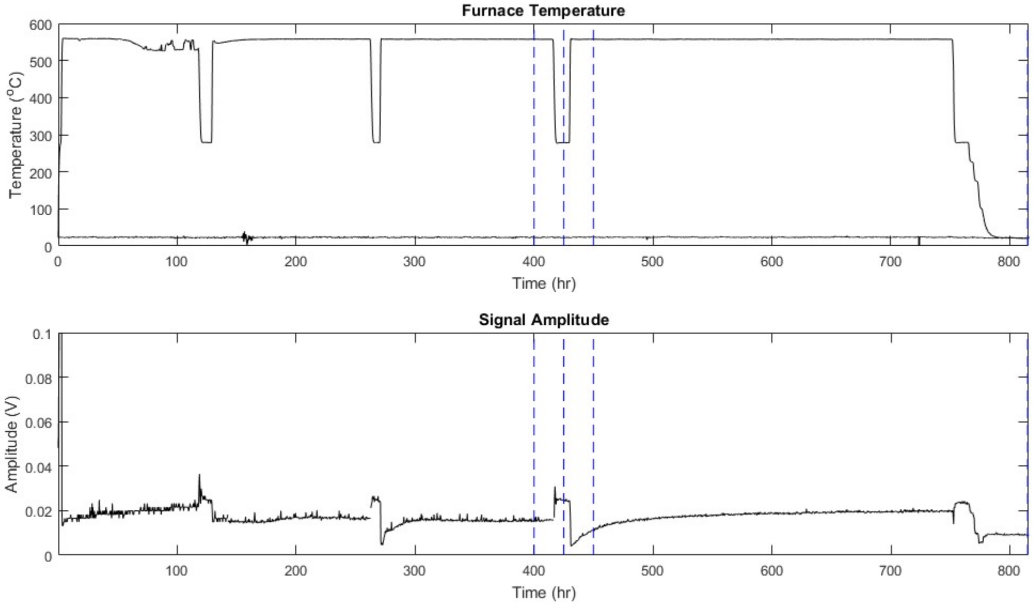

Figure 2. Temperature and signal amplitude during testing

Figure 2 shows that the signal amplitude during steady state operations is relatively stable, indicating that the design may be capable of long-term operation in a sodium fast reactor. The signal amplitude is seen to drop as the temperature initially increases after a thermal cycle. This behaviour is attributed to differential thermal expansion among the various materials used in the transducer fabrication. Evidence for this is in the fact that the signal stabilizes and resumes its initial strength and sensitivity as the entire probe returns to a thermal equilibrium at 550ºC (1022ºF).

The dashed lines in Figure 2 indicate the times at which the waveforms in Figure 3 were collected. The amplitude of the waveform is measured within the time window highlighted on each of the waveforms in Figure 3 and is from the back surface of a block that the transducer was placed on during the test (the block was also placed in the furnace and the transducer was in continuous contact with it for the duration of the test).

The sensor seemed to suffer non-recoverable damage when cooled below 200ºC at the end of the test. While glass solder assists in consistent coupling of the piezoelectric element to the faceplate, it was discovered that the lead-content of the glass solder impacted the long-term integrity of the probe. Upon examination of the probe after testing, it was found that the lead, when reaching temperatures above 400ºC, reacts with the gold electrodes that are sputtered onto the probe. This reaction damages the electrodes and creates non-uniform electrical contact across the face of the piezoelectric element. This effect was seen on the top surface of the piezoelectric element as well, where the lead was able to wick itself into the interface between the piezoelectric element and backing material. Figure 4 shows the by-products from this reaction; this form of damage was not visible in previous testing without the glass solder. While this shouldn't impact monitoring in a reactor environment, it is a concern that may lead to further design changes. Different electrode materials that do not react with lead, such as nickel, are being evaluated as alternatives for sputtering onto the piezoelectric elements.

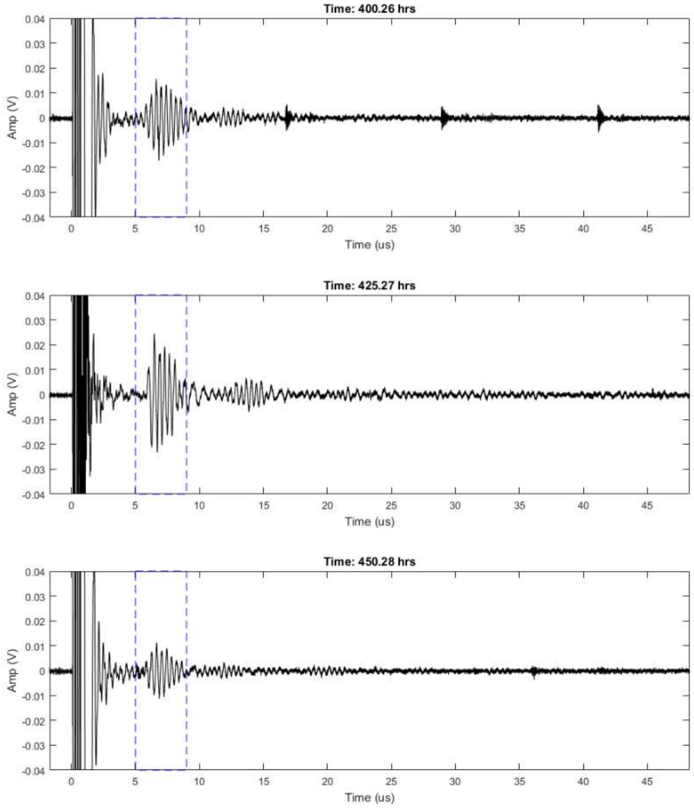

Figure 3. Individual waveforms measured around the 425-hr thermal cycle

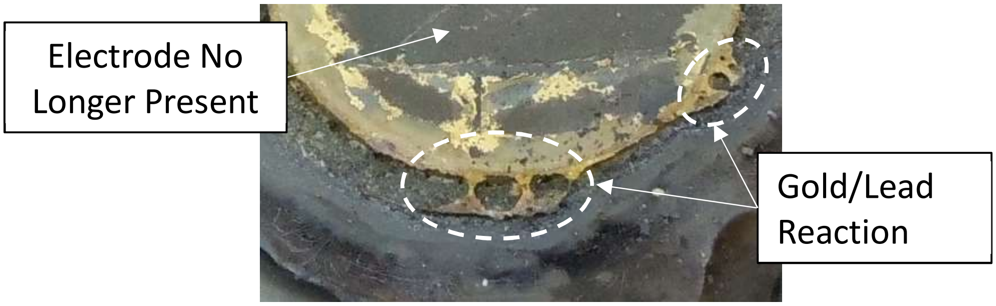

Figure 4. Lead reaction with gold electrodes on the piezo

CONCLUSION

Ultrasonic NDE methods may be adapted for both inspection and continuous monitoring in ANLWRs. However, issues related to sensor survivability impact the ability to reliably assess component condition. Advances in sensor design are needed to enable continuous online monitoring in ANLWRs.

Recent advances in ultrasonic design indicate that sensor material selection and the transducer material selection are important for developing survivable transducers. Long-term laboratory tests indicate stable performance during steady state operation (steady state thermal environment) with some deviations during transients that are attributed to residual differences in thermal expansion coefficients in the materials used in the transducer design. While the performance at temperature was as desired, subsequent cool-down indicated potential problems with chemical compatibility of some of the materials (glass solder and electrode material) that will need to be addressed in future work.

FUTURE WORK

Based on current results, a refinement to the probe design is necessary and will be evaluated. Specifically, different techniques for joining the piezoelectric element to the housing are needed and brazing, among other options, will be examined. Additional design changes to achieve higher operating temperatures are needed, and will be evaluated, along with the compatibility of these designs with other aspects of typical ANLWR environments (chemical compatibility with coolant material, performance under fast neutron irradiation). The reliability of these probes for detecting cracking and monitoring microstructure changes will also need to be evaluated.

ACKNOWLEDGEMENTS

This research was supported by the US Department of Energy Office of Nuclear Energy’s Advanced Reactor Technology program.

REFERENCES

Bentley, P. G. (1981). "A Review of Acoustic Emission for Pressurised Water Reactor Applications," *NDT International,* **14**(6): 329-335.

Bermes, C., Kim, J.-Y, Qu, J. and Jacobs, L. J. (2008). "Nonlinear Lamb waves for the detection of material nonlinearity," *Mechanical Systems and Signal Processing,* **22**(3): 638-646.

Bilgunde, P. N. and Bond, L. J. (2015). "Effect of Thermal Degradation on High Temperature Ultrasonic Transducer Performance in Small Modular Reactors," *Physics Procedia*, **70**: 433-436.

Bond, L. J. (1988). "Review of Existing NDT Technologies and Their Capabilities," *Proceedings of AGARD/SMP Review of Damage Tolerance for Engine Structures: 1. Non-Destructive Evaluation*. Luxembourg, Advisory Group for Aerospace Research and Development (AGARD), France**:** 16.

Bond, L. J., Doctor, S. R. and Taylor, T. T. (2008). "Proactive Management of Materials Degradation – A Review of Principles and Programs." Richland, Washington, Pacific Northwest National Laboratory.

Cantrell, J. H. and Yost, W. T. (2001). "Nonlinear Ultrasonic Characterization of Fatigue Microstructures," *International Journal of Fatigue*, **23**: 487-490.

Chang, Y. I., Grandy, C., Lo Pinto, P. and Konomura, M. (2005). "Small Modular Fast Reactor Design Description." Argonne, Illinois, Argonne National Laboratory.

Daw, J., Palmer, J., Ramuhalli, P. Keller, P. E., Montgomery, R. O., Chien, H. T., Tittman, B., Reinhardt, B., Kohse, G. E. and Rempe, J. (2015). "Ultrasonic Transducer Irradiation Test Results," *ANS Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies (NPIC-HMIT) 2015*. Charlotte, North Carolina, American Nuclear Society, La Grange Park, Illinois.

Daw, J., Rempe, J., Ramuhalli, P., Montgomery, R., Chien, H. T., Tittmann, B. and Reinhardt, B. (2012). "NEET In-Pile Ultrasonic Sensor Enablement-FY 2012 Status Report." Idaho Falls, Idaho, Idaho National Laboratory.

Diaz, A. A., Chamberlin, C. E., Edwards, M. K., Hagge, T. J., Hughes, M. S., Larche, M. R., Mathews, R. A., Neill, K. J. and Prowant, M. S. (2016). "FY16 Status of Immersion Phased Array Ultrasonic Probe Development and Performance Demonstration Results for Under Sodium Viewing." Richland, Washington, Pacific Northwest National Laboratory.

Doctor, S. R. (2008). "The History and Future of NDE in the Management of Nuclear Power Plant Materials Degradation," *Proceedings of the ASME 2008 Pressure Vessels and Piping Division Conference*. Chicago, Illinois, American Society of Mechanical Engineers, New York. **5:** 197-207.

Doctor, S. R., Bruemmer, S. M., Good, M. S., Charlot, L. A., Taylor, T. T., Boyd, D. M., Deffenbaugh, J. D., and Reid, L. D. (1989). "Utilization of Ultrasonic Measurements to Quantify Aging-Induced Material Microstructure and Property Changes," *Nondestructive Monitoring of Materials Properties Symposium*. Boston, Massachusetts, Materials Research Society, Pittsburgh, Pennsylvania**:** 143-149.

Ensminger, D. and Bond, L. J. (2011). *Ultrasonics: Fundamentals, Technology and Applications, Third Edition (Revised and Expanded)*. Boca Raton, Florida, CRC Press.

Goebbels, K. (1994). *Materials Characterization for Process Control and Product Conformity*. Boca Raton, Florida, CRC Press.

Hutton, P. H., Friesel, M. A. and Dawson, J. F. (1993). "Continuous AE Crack Monitoring of a Dissimilar Metal Weldment at Limerick Unit 1." Washington, DC, U.S. Nuclear Regulatory Commission.

Jax, P. and Ruthrof, K. (1989). "Acoustic Emission Inspections of Nuclear Components Considering Recent Research Programmes," *Nuclear Engineering and Design*, **113**(1): 71-79.

Korsah, K., Kisner, R. A., Britton, C. L., Jr., Ramuhalli, P., Wootan, D. W., A. J. N. C., Diaz, A. A., Hirt, E., Vilim, Chien, R. H. T., Bakhtiari, S., Sheen, S., Gopalsami, S. S., Heifetz, A. Tam, S. W., Park, Y., Upadhyaya, B. R., and Stanford, A. (2016). "Assessment of Sensor Technologies for Advanced Reactors." Oak Ridge, TN, Oak Ridge National Laboratory.

Krautkrämer, J. and Krautkrämer, H. (1990). *Ultrasonic Testing of Materials, 4th Fully Revised Edition*. New York, Springer-Verlag.

Li, Y., S. Hu and Henager, C.H. Jr. (2019). "Microstructure-based model of nonlinear ultrasonic response in materials with distributed defects," *Journal of Applied Physics*, **125**(14): 145108.

Matlack, K. H., Bradley, H. A., Thiele, S., Kim, J.-Y., Wall, J. J., Jung, H. J., Qu, J. and Jacobs, L. J. (2015). "Nonlinear ultrasonic characterization of precipitation in 17-4PH stainless steel," *NDT & E International*, **71**: 8-15.

Matlack, K. H., Wall, J. J., Kim, J.-Y., Qu, J., Jacobs, L. J. and Viehrig, W.-W. (2012). "Evaluation of Radiation Damage Using Nonlinear Ultrasound," *Journal of Applied Physics*, **111**(5): 054911-054911 to 054911-054913.

McCloy, J. S., Montgomery, R.O., Ramuhalli, P., Meyer, R. M., Hu, S. Y., Li, Y., Henager, C. H. Jr. and B. R. Johnson (2013). "Materials Degradation and Detection (MD2): Deep Dive Final Report." Richland, Washington, Pacific Northwest National Laboratory.

Meyer, R. M., Coble, J.B ., Hirt, E. H., Ramuhalli, P., Mitchell, M. R., Wootan, D. W., Berglin, E. J., Bond, L. J. and Henager, C. H. Jr. (2013). "Technical Needs for Prototypic Prognostic Technique Demonstration for Advanced Small Modular Reactor Passive Components." Richland, Washington, Pacific Northwest National Laboratory.

Meyer, R. Ramuhalli, M. P., Bond, L. J., Coble, J. B. and Hirt, E. H. (2013). "Technical Needs for Prognostic Health Management of Passive Components in Advanced Small Modular Reactors," *American Nuclear Society Winter Conference and Technology Expo*. Washington D.C.

Meyer, R. M., Ramuhalli, M. P., Doctor, S. R. and Bond, L. J. (2013). "Qualification Requirements of Guided Ultrasonic Waves for Inspection of Piping in Light Water Reactors," *The 39th Review of Progress in Quantitative Nondestructive Evaluation*, July 15-20, 2012, Denver, Colorado. AIP Conference Proceedings, Melville, NY, American Institute of Physics.

Prowant, M. S., Dib, G., Qiao, H., Good, M. S., Larche, M. R., Sexton, S. S., Ramuhalli, P., A. T. and I. S. (2018). "Preliminary design of high temperature ultrasonic transducers for liquid sodium environments," *AIP Conference Proceedings* **1949**(1): 100006.

Raj, B., Kumar, A. and Jayakumar, T. (2000). "Ultrasonic Spectral Analysis for Microstructural Characterization of Austenitic and Ferritic Steels," *Philosophical Magazine A (UK),* **80**(11): 2469-2487.

Raj, B., Moorthy, V., Jayakumar, T. and Rao, K. B. S. (2003). "Assessment of Microstructures and Mechanical Behaviour of Metallic Materials through Non-destructive Characterisation," *International Materials Reviews*, **48**(5): 273-325.

Raj, B., Mukhopadhyay, C. K. and Jayakumar, T. (2006). "Frontiers in NDE Research Nearing Maturity for Exploitation to Ensure Structural Integrity of Pressure Retaining Components," *International Journal of Pressure Vessels and Piping*, **83**(5): 322-335.

Ramuhalli, P., Coble, J. B., Meyer, R. M. and Bond, L. J. (2013). "Prognostics Health Management and Life Beyond 60 for Nuclear Power Plants," *Future of Instrumentation International Workshop (FIIW)*, October 8-9, 2012, Gatlinburg, Tennessee, Piscataway, NJ, Institute of Electrical and Electronics Engineers, Inc.

Ramuhalli, P., Dib, G., Prowant, M. S., Qiao, H. A., Hirt, E. H., Lissenden, C. J. and Tittmann, B. (2017). "Assessment of Nondestructive Measurement Sensitivity for Selected Measurement Techniques; Advanced Reactor Technology Milestone: M3AT-17PN2301034." Richland, Washington, Pacific Northwest National Laboratory.

Ramuhalli, P., Hirt, E. H., Pitman, S. G., Dib, G., Roy, S., Good, M. S. and Walker, C. M. (2016). "Experimental Design for Evaluating Selected Nondestructive Measurement Technologies – Advanced Reactor Technology Milestone: M3AT-16PN2301043." Richland, Washington, Pacific Northwest National Laboratory.

Ramuhalli, P., Roy, S., Hirt, E. H., Pardini, A. F., Jones, A. M., Deibler, J. E., Pitman, S. G., Tucker, J. C., Prowant, M. and Suter, J. D. (2014). "Local-Level Prognostics Health Management Systems Framework for Passive AdvSMR Components – Interim Report." Richland, Washington, Pacific Northwest National Laboratory.

Runow, P. (1985). "Use of Acoustic Emission Methods as Aids to the Structural Integrity Assessment of Nuclear Power Plants," *International Journal of Pressure Vessels and Piping*, **21**(3): 157-207.

Searfass, C. T., Tittmann, B. R. and Agrawal, D. K. (2009). "Sol-Gel Deposited Think Film Bismuth-Tuitatate Based Transducer Achieves Operation over 600°C," *Proceedings of the 35th Annual Review of Progress in Quantitative Nondestructive Evaluation*. D. O. Thompson and D. E. Chimenti. Chicago, Illinois, AIP Conference Proceedings. **1096**.

Shui, G., Kim, J. -Y., Qu, J., Wang, Y.-S. and Jacobs, L. J. (2008). "A New Technique for Measuring the Acoustic Nonlinearity of Materials Using Rayleigh Waves," *NDT & E International*, **41**(5): 326-329.

Tipireddy, R., Lerchen, M. and Ramuhalli, P. (2017). "Virtual Sensors for Robust On-Line Monitoring (OLM) and Diagnostics," *ANS 10th International Topical Meeting on NPIC-HMIT*. San Francisco.