7-2012

Qualification requirements of guided ultrasonic waves for inspection of piping in light water reactors

R. M. Meyer
Pacific Northwest National Laboratory

P. Ramuhalli
Pacific Northwest National Laboratory

S. R. Doctor
Pacific Northwest National Laboratory

Leonard J. Bond
Iowa State University, bondlj@iastate.edu

Qualification requirements of guided ultrasonic waves for inspection of piping in light water reactors

Abstract

It is anticipated that guided ultrasonic wave (GUW) techniques will eventually see widespread application in the nuclear power industry as there are several near-term and future needs that could benefit from the availability of GUW technologies. Already, GUW techniques are receiving consideration for inspecting buried piping at nuclear power plants and future applications may include several Class 1 and 2 components. To accept the results of a nondestructive examination of safety critical components, the U.S. Nuclear Regulatory Commission requires that the examinations be performed using qualified equipment, personnel, and procedures. As the use of GUW techniques becomes more frequent, qualification may be required. Performance demonstration has been the approach to qualifying conventional NDE methods in the nuclear power industry. This paper highlights potential issues and research needs associated with facilitating GUW qualification for the nuclear power industry. Parametric studies of essential inspection parameters are necessary to understand their influence on inspection performance. The large volume sampling capability introduces several challenges for qualifying GUW techniques including the quantification of performance, potential interference caused by the presence of multiple flaws in the inspection region, and the practicality of manufacturing several large qualification specimens. Computer simulation may have a significant role in reducing the experimental burden associated with qualifying GUW techniques for nuclear power plant examinations.

Keywords

fission reactor design, fission reactor safety, light water reactors, nondestructive testing, nuclear power stations, ultrasonic waves, nondestructive evaluation, QNDE, Aerospace Engineering

Disciplines

Aerospace Engineering | Materials Science and Engineering | Structures and Materials

Comments

This article appeared in *AIP Conference Proceedings* 1511 (2013): 1662–1669 and may be found at http://dx.doi.org/10.1063/1.4789241.

Qualification requirements of guided ultrasonic waves for inspection of piping in light water reactors

R. M. Meyer, P. Ramuhalli, S. R. Doctor, and L. J. Bond

Citation: AIP Conf. Proc. **1511**, 1662 (2013); doi: 10.1063/1.4789241

View online: http://dx.doi.org/10.1063/1.4789241

View Table of Contents: http://proceedings.aip.org/dbt/dbt.jsp?KEY=APCPCS&Volume=1511&Issue=1

Published by the American Institute of Physics.

QUALIFICATION REQUIREMENTS OF GUIDED ULTRASONIC WAVES FOR INSPECTION OF PIPING IN LIGHT WATER REACTORS

R. M. Meyer[1], P. Ramuhalli[1], S. R. Doctor[1], and L. J. Bond[2]

[1]Applied Physics, Pacific Northwest National Laboratory, Richland, WA 99352
[2]Center for Nondestructive Evaluation, Iowa State University, Ames, IA 50011

ABSTRACT. It is anticipated that guided ultrasonic wave (GUW) techniques will eventually see widespread application in the nuclear power industry as there are several near-term and future needs that could benefit from the availability of GUW technologies. Already, GUW techniques are receiving consideration for inspecting buried piping at nuclear power plants and future applications may include several Class 1 and 2 components. To accept the results of a nondestructive examination of safety critical components, the U.S. Nuclear Regulatory Commission requires that the examinations be performed using qualified equipment, personnel, and procedures. As the use of GUW techniques becomes more frequent, qualification may be required. Performance demonstration has been the approach to qualifying conventional NDE methods in the nuclear power industry. This paper highlights potential issues and research needs associated with facilitating GUW qualification for the nuclear power industry. Parametric studies of essential inspection parameters are necessary to understand their influence on inspection performance. The large volume sampling capability introduces several challenges for qualifying GUW techniques including the quantification of performance, potential interference caused by the presence of multiple flaws in the inspection region, and the practicality of manufacturing several large qualification specimens. Computer simulation may have a significant role in reducing the experimental burden associated with qualifying GUW techniques for nuclear power plant examinations.

Keywords: Guided Ultrasonic Waves, Performance Demonstration, Qualification, Nuclear Power Plant
PACS: 81.70.-q, *43.40.Le, *43.35.Zc, 81.70.Cv, 28.41.-i, 28.50.-k

INTRODUCTION

Despite the relative maturity of guided ultrasonic wave (GUW) techniques for certain applications (e.g., pipeline examinations), it may still be regarded as an emerging technology in many fields such as in the nuclear power industry because the consequences of accidents merit a relatively cautious approach to the adoption of new nondestructive examination (NDE) methods. However, it is anticipated that GUW techniques will eventually see widespread application in the nuclear power industry as there are several near-term and future needs that could benefit from the availability of GUW technologies.

The 39th Annual Review of Progress in Quantitative Nondestructive Evaluation
AIP Conf. Proc. 1511, 1662-1669 (2013); doi: 10.1063/1.4789241

GUW techniques are receiving considerable attention as a means to inspect the integrity of buried piping at nuclear power plants (NPPs). This consideration is part of an industry-wide response to recent occurrences of tritium leakage from buried piping at NPPs. Although the instances of leakage have not exceeded U.S. Nuclear Regulatory Commission (NRC) limits, they have generated significant stakeholder concern [1, 2]. The industry has responded to concerns about buried piping by forming the Underground Piping and Tanks Integrity Initiative in 2010 [3]. A goal of this initiative is to provide "reasonable assurance" of the structural and leak integrity of underground pipes and tanks through risk ranking, indirect assessments, and direct examinations.

Beyond the inspection of buried or underground piping and tanks, GUW techniques may have a significant role to play in sustaining the operation of the current fleet of light water reactors (LWRs). In the United States, an initial 40-year operating license is granted for NPPs with the opportunity to apply for multiple 20-year license extensions. The average age of the 104 reactors in the United States' commercial nuclear power fleet is 32 years. Already, 73 of the these reactors have received an initial 20-year license renewal for operation (30 more applications are pending or expected) and 10 of these have already entered the first phase of long-term operation (LTO) (age between 40 and 60 years) [4]. Materials degradation in passive components as a consequence of aging is considered a significant challenge to ensuring the safe operation of NPPs as they enter phases of LTO, and the management of materials degradation in several components through the application of NDE technologies to assess component condition is important to mitigating the consequences of aging degradation. Potential applications for GUW techniques include monitoring of Class 1 and 2 piping, steam generator tubes, the reactor pressure vessel (RPV) welds, RPV penetrations, liner plates and reinforcing steel in concrete containments structures, etc.

In addition to the current fleet of operating reactors, many potential applications of GUW techniques exist for small modular reactors (SMRs) [5] and advanced reactor concepts. SMRs, in particular, present access challenges due to their integral designs while several advanced reactor concepts, such as the Pebble Bed Modular Reactor (PBMR), refuel online or have extended periods of operation between refueling outages, decreasing the opportunity for inspection and maintenance [6].

To accept the results of a nondestructive examination of safety-critical components, the NRC requires that the examinations be performed using qualified equipment, personnel, and procedures. As the use of GUW techniques becomes more widespread in the nuclear power industry, performance demonstration may be required by industry to qualify GUW examinations of safety-critical components. Currently, an ASME Boiler and Pressure Vessel (B&PV) Code Section V working group is developing methodology requirements for GUW techniques. This paper highlights potential issues and research needs associated with facilitating GUW qualification for the nuclear power industry by reviewing inservice inspection (ISI) practice and the evolution of qualification requirements for conventional ultrasonic techniques. This is followed by an overview of factors that impact the effectiveness and reliability of NDE examinations, a consideration of acceptance criteria, and a description of the relevant state-of-the-art for GUW techniques.

INSERVICE INSPECTION IN THE NUCLEAR POWER INDUSTRY

In the nuclear power industry, components are categorized as safety or non-safety according to the safety risk they pose to the public in the event of a failure. Further sub-classifications of safety components include: Class 1 – Systems in direct contact with the coolant water; Class 2 – Systems that remove primary heat or are required to actuate in an emergency; Class 3 – Systems that provide support functions for other systems (e.g., service water, steam conversion systems). ISI is part of a defense-in-depth philosophy to help ensure the structural integrity and leak integrity of safety components to ensure overall plant safety [7]. Performing NDE of safety components is required by Title 10, Part 50 of the Code of Federal Regulations through its endorsement of the ASME B&PV Code rules for ISI (Section XI). The ASME B&PV Code specifies the type of examinations (volumetric, surface, or visual), frequency of examinations, and sampling criteria to use for each class of components. Essentially, the most stringent requirements are placed on the examination of Class 1 components, while Class 2 components are subject to less stringent requirements than Class 1, and Class 3 components are subject to less stringent requirements than Class 2 components. The ASME B&PV Code does not provide rules for performing ISI of balance-of-plant (BOP) components.

EVOLUTION OF NDE QUALIFICATION IN THE NUCLEAR POWER INDUSTRY

A historical overview of NDE research for managing degradation in commercial NPPs is provided by [7]. It is noted that ASME requirements to address examination of nuclear power plant components were developed in the 1960s and were originally prescriptive in nature. Prescriptive code requirements enabled the industry to quickly adopt ISI practices but created a barrier to the adoption of better practices by the industry as they became available. Several parametric and round-robin studies were performed beginning in the 1970s to better understand the effectiveness and reliability of conventional ultrasonic testing (UT) techniques and to assess the capabilities of emerging techniques. Studies were performed by the Pressure Vessel Research Council of the Welding Research Council, by the NRC, and also through the Programme for the Inspection of Steel Components (PISC) trials, and the UK Atomic Energy Authority Defect Detection Trials. These studies showed that UT performance depended on several variables including personnel, equipment, procedures, and environments, and that the effectiveness and reliability of UT examinations are highly skill-dependent. In addition, field experience and round-robin studies indicated that improvements in UT reliability were needed [7].

The performance demonstration (PD) concept emerged as a method to improve the reliability and effectiveness of field NDE to ensure NDE effectiveness through a stringent qualification process. Performance demonstration requirements were discussed at NRC workshops in 1984, which lead to the creation of Appendix VIII to Section XI of the ASME B&PV Code [7]. Industry has moved to implement the Appendix VIII requirements through the industry Performance Demonstration Initiative (PDI) administered by the Electric Power Research Institute (EPRI) [8]. Currently, the NRC establishes requirements for examinations to ensure the quality of the examination results. Essentially, the NRC establishes that examinations must be performed by qualified personnel using qualified equipment and qualified procedures [9]. Performance demonstration requirements in Appendix VIII assume that an inspector's ability to detect flaws can be described by probability of detection (POD) and false call probability (FCP) parameters where FCP is the probability of incorrectly identifying a flaw in a "blank" or flaw-free specimen. The objective of PD conducted in accordance with Appendix VIII is to distinguish inspector performance based on acceptable POD and FCP metrics, and the PD is implemented as a statistically based screening process to pass inspectors with acceptable performance and fail inspectors with unacceptable performance [7]. Separate demonstrations are required to qualify personnel and to qualify equipment and procedure. In Appendix VIII, blind demonstrations are required to qualify personnel, equipment, and procedure. Separate ASME Code Cases have been developed to allow open procedure/equipment demonstrations. Code Case N780 allows open demonstrations to qualify the equivalency of substituted equipment and Code Case N775 allows the performance of open procedure/equipment demonstrations of eddy current techniques used in tandem with qualified ultrasonic techniques for ID pipe inspections. Benefits of open procedure/equipment testing include an opportunity for the operator to receive feedback from the PD administrator and improve the procedure. Efforts to develop PD requirements have concentrated on conventional UT techniques, but there may be a need to develop similar requirements for other NDE methods. The application of NDE through online monitoring (OLM) versus periodic examination also presents unique factors that will need to be considered by qualification programs.

ESSENTIAL FLAW PARAMETERS FOR QUALIFICATION SPECIMENS

An extensive review of the influence of essential flaw parameters on UT examinations is provided by [10]. This review is performed considering the compilations of crack characteristics by the Swedish Nuclear Power Inspectorate (SKI) [11, 12] and from the perspective of validating or confirming the representativeness of flaw specimens for NDE qualification. They considered the effects of crack size, crack morphology, fracture surface roughness, fracture surface separation (crack width), crack orientation, and the effects of a crack filled with water or debris. It is noted that a rough fracture surface results in significant diffuse scattering of the incident beam; whereas, a smooth fracture surface results in mostly specular reflection [13]. Thus, rough fracture surfaces may be advantageous for the detection of cracks oriented at glancing angles with respect to the probe. On the other hand, rough fracture surfaces make sizing more difficult based on amplitude techniques. The crack opening displacement (COD) can impact detection as tightly closed cracks may enable transmission of elastic waves through the crack faces. Observations of this effect have been reported for fatigue cracks with CODs below 10 μm [14]. A similar review has been performed by SKI [15] to assess the influence of essential flaw parameters on several NDE methods including UT, eddy current testing (ET), and radiographic testing (RT). The purpose of this review was also to understand the essential flaw parameters to guide the manufacturing of representative qualification specimens. It was concluded that defect geometry, orientation, and size all have a significant influence on ET response. For UT, it was concluded that flaw parameters such as position (depth), orientation, size, surface roughness, closure, and crack tip radius can influence the UT response. For the performance demonstration process to be effective, qualification specimens should closely imitate specimen conditions in the field [7]. As a consequence, some efforts have been focused on "growing" realistic flaws in qualification specimens. A process for growing stress corrosion cracks (SCC) in qualification specimens has been developed, referred to as the MISTIQ process [16]. Methods have also been devised to grow cracks in specimens through thermal fatigue [17, 18].

ACCEPTANCE CRITERIA

As previously alluded to, GUW techniques are under consideration by industry for assessing the integrity of underground or buried piping and it is anticipated that future applications of GUW to the nuclear power industry may include the assessment of Class 1 and Class 2 safety components. Buried piping will be subject to bending moments that generate an axial stress as a consequence of loading caused by soil movement, surface traffic, or seismic activity. Class 1 components will be subject to radial stresses from pressurization, weld residual stresses, and bending stresses caused by thermal loadings. Corrosion is the most likely manifestation of degradation in buried piping, while cracks are anticipated to be a major target of GUW examinations in Class 1 components. The anticipated loading conditions and flaw manifestation will influence the criteria by which inspection results are judged. Studies have been conducted by Battelle Columbus [19] and Southwest Research Institute (SWRI) [20] to observe the impact of complex loadings caused by internal pressurization and bending moments causing axial stress loading to failure. Under these complex loading conditions, it was found that failure depended in a complex manner on features of corrosion flaws. These features include the dimensions of corrosion patches and the distribution of collocated corrosion patches. For cracks in Class 1 components the depth of flaws is considered the most relevant parameter with respect to structural integrity.

RELEVANT STATE-OF-THE-ART FOR GUW SYSTEMS

Long-range pipe inspection devices were initially developed to monitor piping for corrosion defects in petrochemical and chemical industries [21]. Axisymmetric guided ultrasonic wave modes can be generated using a ring-shaped array of piezoelectric elements wrapped around the circumference of the pipe for inspection. Characterization studies have been conducted on pipes using circumferential notches to simulate flaws [22]. These studies have parametrically examined the response of L(0,2) and T(0,1) modes to changes in notch dimensions and provide a good understanding of the behavior of axisymmetric modes in response to interactions with notches. Commercial GUW systems have been developed mostly for performing long-range inspections of pipelines in the oil and gas industries. Two systems currently on the market include the Teletest Focus™ system from Plant Integrity Ltd., which is a wholly owned subsidiary of TWI (http://www.twi.co.uk) and the Wavemaker™ system from GUL (http://www.guided-ultrasonics.com/) [23]. Both systems are based on technology developed at Imperial College in the UK. The systems excite axially guided wave modes using a ring of piezoelectric transducers installed around the full pipe circumference. An inflatable transducer ring provides the necessary force to couple the piezoelectric elements to the surface of the pipe. These systems have typical ranges of 10's of meters depending on pipeline conditions. The sensitivity of these systems is typically reported to be approximately 5% cross-section loss [23] with claims as low as 1% cross-section loss under ideal conditions (from http://www.guided-ultrasonics.com/). Commercial systems are also available that are based on magnetostrictive sensor (MsS) technology developed at Southwest Research Institute and licensed by M. K. C. Korea (http://www.mkckorea.com/english.htm) [23]. The M. K. C. Korea website displays several MsS probes for inspection of both pipelines and plate type components.

Alleyne and Cawley [24] investigated the interaction of individual Lamb waves with a variety of notch defects using finite-element analysis and bench-scale tests. The sensitivity is shown to be dependent on a number of factors including the frequency-thickness product, the mode type, the mode order, and defect geometries. The interaction of the fundamental symmetrical Lamb mode (S0) with cracks in aluminum plates was examined by LeClezio et al. [25]. The studies indicated that cracks behave similarly to thin notches. Model decomposition and finite element modeling (FEM) have been used to study the interaction of fundamental shear horizontal (SH0) modes from defects in plates [26]. This work examined the impact of notch depth and frequency on reflection from notches and considered the use of thin notches to simulate cracks. It is noted that the interaction of nonpropagating modes between crack faces could significantly impact the scattering behavior of cracks versus approximating notches. Shivaraj et al. [27] investigated a circumferentially guided wave system for detection and imaging pitting corrosion in piping at pipe supports regions. The detection of pinholes as small as 1.5 mm in diameter and 20% through-wall depth is reported. An inline inspection system has recently been developed for the inspection of buried piping at nuclear power plants. The system, developed by Wesdyne, is referred to as the Lamb Wave Crawler [28] and operates by launching Lamb waves circumferentially in pipe walls. The system can map the condition of the pipe by measurements obtained from the inner pipe surface.

DISCUSSION

Definition of parameters to quantify the performance of GUW inspectors is a prerequisite to implementing performance demonstrations. POD and FCP are used to quantify the performance of conventional NDE technologies but several aspects of GUW complicate this approach. GUW techniques often sample relatively large volumes of material so POD curves have to consider the distance of the flaw from the sensor as well as the features of the flaw such as size, orientation, and geometry. In addition, the ability of GUW to sample relatively large volumes of material introduces the possibility that multiple flaws exist within the sampled volume. In this case, it becomes necessary to determine the influence of additional flaws on the POD for the target flaw.

Parametric studies are needed to assess the influence of essential variables on GUW performance. Some effort has already been devoted to studying the influence of notch dimensions on the response of axisymmetric guided wave modes [22]. Similar studies should be performed on specimens with more realistic flaws and the accuracy of approximating cracks with thin notches should be more thoroughly explored. Parametric studies should also include signal analysis techniques as they are anticipated to have an influence on the performance of GUW examinations. Computer simulation may have a significant role in determining the influence of essential variables on GUW performance and can potentially limit experimental efforts to benchmarking cases.

GUW techniques may be used for screening and/or characterization applications. Decisions regarding the necessity of a follow-up characterization examination are made based on the results of screening examinations. The zone or region for which the GUW examination can produce acceptable results will need to be defined taking into account welds, bends, and other geometry or loading factors that can influence performance. A performance demonstration will require qualification specimens that encompass the full region or zone of examination, potentially leading to qualification specimens that are very large potentially limiting the practicality of performance demonstrations for large examination zones. Computer simulation may have a role in supporting efforts to qualify GUW procedures for large specimens.

CONCLUSIONS

The U.S. NRC requires that the examinations be performed using qualified equipment, personnel, and procedures to accept the results of a nondestructive examination of safety important components.. As the use of GUW techniques becomes more widespread in the nuclear power industry, performance demonstration may be required to qualify GUW examinations of safety important components. Understanding essential examination variables and how they can impact the performance of GUW exams is a prerequisite to qualification. The large volume sampling capability introduces several challenges for qualifying GUW techniques and the need for large qualification specimens could limit the practicality of performance demonstrations. Computer simulations may have a significant role in relieving some of the experimental burdens associated with qualifying GUW techniques for the nuclear power industry.

ACKNOWLEDGEMENTS

This work was supported through the Reactor Aging Management (RAM) Focus Area of the Pacific Northwest National Laboratory (PNNL) Sustainable Nuclear Power Initiative (SNPI). PNNL is a multi-program national laboratory operated by Battelle Memorial Institute for the US Department of Energy under DE-AC06-76RLO 1830.

REFERENCES

1. NRC, "NRR Action Plan, Revision 1, Buried Piping," ADAMS Accession No. ML102590171, U.S. Nuclear Regulatory Commission, Washington, D.C., 2010.
2. M. L. Wald, "Vermont Senate Votes to Close Nuclear Plant," in *The New York Times* (February 24, 2010). http://www.nytimes.com/2010/02/25/us/25nuke.html?pagewanted=all.
3. NEI, "Guideline for the Management of Underground Piping and Tank Integrity," NEI 09-14, Rev. 1, Nuclear Energy Institute (NEI), Washington, D.C., 2010.
4. NEI, "Resources & Stats, License Renewal," Accessed August 30, 2012, Nuclear Energy Institute, Washington, D.C., http://www.nei.org/resourcesandstats/nuclear_statistics/licenserenewal/.
5. D. T. Ingersoll, *Progr. Nucl. Energ.* **51**, 589-603 (2009).
6. INL, "NGNP High Temperature Materials White Paper," INL/EXT-09-17187, Idaho National Laboratory, Idaho Falls, Idaho, 2010.
7. S. R. Doctor, in *Proceedings of the ASME 2008 Pressure Vessels and Piping Division Conference*, Chicago, Illinois, American Society of Mechanical Engineers, New York, 2008, pp. 197-207.
8. T. L. Moran, P. Ramuhalli, A. F. Pardini, M. T. Anderson and S. R. Doctor, "Replacement of Radiography with Ultrasonics for the Nondestructive Inspection of Welds - Evaluation of

Technical Gaps - An Interim Report," PNNL-19086, Pacific Northwest National Laboratory, Richland, Washington, 2010.
9. 10 CFR 50.55a., "Codes and standards." Code of Federal Regulations, U.S. Nuclear Regulatory Commission, Washington, D.C., 2012.
10. M. Kemppainen and I. Virkkunen, *J. Nondestr. Eval.* **30** (3), 143-157 (2011).
11. P. Ekstrom and J. Wåle, "Crack Characterization for In-service Inspection Planning," SKI Report 95:70, Swedish Nuclear Power Inspectorate, Stockholm, Sweden, 1995.
12. J. Wåle, "Crack Characterisation for In-service Inspection Planning - An Update," SKI Report 2006:24, Swedish Nuclear Power Inspectorate, Stockholm, Sweden, 2006.
13. J. A. Ogilvy, *Ultrasonics* **27** (2), 69-79 (1989).
14. K. Iida, K. Takumi and A. Naruse, in *The Ninth International Conference on Nondestructive Evaluation in the Nuclear Industry*, Tokyo, Japan, 1988, pp. 563-567.
15. H. Wirdelius and E. Österberg, "Study of Defect Characteristics Essential for NDT Testing Methods ET, UT, and RT," SKI Report 00:42, Swedish Nuclear Power Inspectorate, Stockholm, Sweden, 2000.
16. W. Daniels and D. Ludlow, in *8th International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurised Components*, Berlin, Germany, 2010.
17. M. Kemppainen, "Realistic Artificial Flaws for NDE Qualification - A Novel Manufacturing Method Based on Thermal Fatigue," Ph.D. Thesis, Helsinki University of Technology, 2006.
18. I. Virkkunen, "Thermal Fatigue of Austenitic and Duplex Stainless Steel," Ph.D. Thesis, Helsinki University of Technology, 2001.
19. D. R. Stephens, T. A. Bubenik and R. B. Francini, "Residual Strength of Pipeline Corrosion Defects Under Combined Pressure and Axial Loads," NG-18 Report No. 216, Battelle, Columbus, Ohio, 1995.
20. M. F. Kanninen, A. E. Crouch, H. Kwun, S. C. Grigory, S. Roy and K. V. Pagalthivarthi, "Development of Methodologies for Determining the Integrity of Corroded Pipelines, Phase II Final Report, Volume 1," SwRI No. 06-3758, Southwest Research Institute, San Antonio, Texas, 1992.
21. M. J. S. Lowe, D. N. Alleyne and P. Cawley, *Ultrasonics* **36** (1–5), 147-154 (1998).
22. A. Demma, P. Cawley, M. Lowe, A. G. Roosenbrand and B. Pavlakovic, *NDT&E Intl.* **37** (3), 167-180 (2004).
23. M. J. S. Lowe and P. Cawley, "Long Range Guided Wave Inspection Usage - Current Commercial Capabilities and Research Directions," Imperial College, London, 2006.
24. D. N. Alleyne and P. Cawley, *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control* **39** (3), 381-397 (1992).
25. E. Le Clézio, M. Castaings and B. Hosten, *Ultrasonics* **40** (1–8), 187-192 (2002).
26. A. Demma, P. Cawley and M. Lowe, *J. Acoust. Soc. Am.* **113** (4), 1880-1891 (2003).
27. K. Shivaraj, K. Balasubramaniam, C. V. Krishnamurthy and R. Wadhwan, *J. Pres. Vessel Technol.* **130**, 021501-021501 to 021502-021511 (2008).
28. WesDyne, "Lamb Wave Crawler", Accessed August 30, 2012, product literature, http://www.westinghousenuclear.com/Products_&_Services/docs/flysheets/NS-FS-0142.pdf