WHITE PAPER

TECHNICAL BASIS FOR PROPOSED ALTERNATE REQUIREMENTS FOR ULTRASONIC EXAMINATION OF CAST AUSTENITIC PIPING WELDS FROM THE OUTER DIAMETER (OD) SURFACE

1.0 INTRODUCTION

Piping welds that join cast austenitic material to the same material or to other materials, such as wrought carbon steel, low alloy steel, or wrought austenitic steel are not addressed in Section XI, Appendix VIII component qualification supplements. The 'in course of preparation' note in Table VIII-3110-1 for this type of material mandates that the Owner apply the requirements of Appendix III as supplemented by Table I-2000-1, for the ultrasonic examination of these components. Currently such requirements do not adequately address the complexity of ultrasonically examining cast austenitic material. While certain improvements in rules are found in Appendix III, Supplement 1, these rules do not reflect the knowledge that has been gained in the last thirty plus years for achieving the best available ultrasonic examination on such materials and associated welds.

The proposed alternate ultrasonic test requirements are intended to define in more specific terms the methods, equipment and knowledge needed to detect and size flaws in cast austenitic material. These alternate requirements are specific to Appendix III and include a proposed new supplement, which is dedicated to cast austenitic materials and their associated welds. These requirements are provided in a manner consistent with the format of Appendix III, Supplement 1, with existing Appendix III criterion being substituted by special or additional requirements where appropriate.

The technical basis for these proposed alternative ultrasonic test requirements are defined below.

2.0 DISCUSSION OF TECHNICAL BASIS

The intent of this section is to provide justification for the proposed alternative ultrasonic test requirements.

2.1 Separation of Dissimilar Metal and Cast Austenitic Weld Ultrasonic Examination Requirements

While it is recognized that both dissimilar metal and cast austenitic welds are coarse grained, anisotropic structures, the difference is that additional detrimental beam/grain interactions are associated with the coarse grained and anisotropic cast austenitic base material. For dissimilar metal welds comprised of high alloy steels, high nickel steels, wrought carbon or low alloy steels, and wrought austenitic steels, the base material is essentially transparent to significant beam/grain interactions and, as such, performance demonstration to the current requirements of Appendix VIII, Supplement 10 are achievable. This higher level of performance for dissimilar metal welds is the reason for maintaining the performance demonstration requirement from one side of the weld (i.e. Appendix VIII, Supplement 10) when the opposite side of the weld is a cast austenitic material.

It is also recognized that cast austenitic material needs to be treated differently with respect to casting methods and casting parameters since the microstructure may be comprised of various grain sizes and shapes as reported in Reference 4.1. Randomly equiaxed, columnar and mixed grain (equiaxed and columnar) structures may exist. The in-situ determination of the microstructure for the materials to be examined has been attempted with only limited success [Refs. 4.2 – 4.7]. For simplistic purposes, the differences in cast austenitic material is divided into statically cast and centrifugally cast consistent with the material being fabricated in a stationary sand-cast type mold (typically fittings such as elbows) or with the material fabricated in a rotating mold (typically piping), respectively.

2.2 Search Unit Selection

Appropriate search units for use on cast austenitic materials have been investigated since the mid 1970's. Generally, until 2005, the search unit type has been a conventional ultrasonic test search unit containing single or multiple monolithic piezoelectric elements with active crystal areas of 0.75 to 1.75 square inches (485 – 1130 mm^2). Such units have been used to propagate 40° - 45° refracted longitudinal waves in a pulse-echo or transmit-receive mode and have a nominal test frequency of 0.5 MHz – 1.5 MHz. The transmit-receive units were fitted to contoured wedges that had a roof or squint angle to achieve theoretical acoustic focusing in the material, at or near the opposite wall surface, based on modeling in isotropic material. Such search units have been generally used in a manual mode [Refs. 4.8 – 4.14].

From roughly 2005 to the present, investigations have concentrated on the use of multi-element, phased array UT search units with total apertures (active aperture x passive aperture) ranging from 0.36 to 5.46 square inches (242 – 3522 mm^2) depending on the thickness of the cast austenitic material. Such search units are used to propagate 30° - 60° refracted longitudinal waves in transmit-receive mode and have a nominal test frequency of 0.5 MHz – 2.0 MHz. The integral and individual wedges associated with these search units are contoured consistent with the component surface. The focal laws are created to focus in the material, at or near the opposite wall surface assuming an isotropic material. These search units have been successfully used in an automated (encoded) scanning mode [Refs. 4.15, 4.16, 4.20 and 4.22].

Such search unit characteristics are consistent with the following technical reasoning:

a) **Dual, Transmit-Receive Refracted Longitudinal Waves**:

Refracted longitudinal waves are less affected by grain interactions, at a given test frequency, than shear waves due to their longer wavelengths. Grain interactions increase as the wavelength decreases (and frequency increases). Whereas the refraction of longitudinal waves also results in a shallower angle shear wave component, the shear wave component is attenuated with the longitudinal wave component being the dominant mode. The dual transmit-receive mode of operation allows for concentration of sound energy in a narrower area with scattering associated with grain boundaries directed preferentially away from the receiving element. In addition, any unwanted wedge internal reflections are minimized in this manner.

b) **Contoured Wedges**:

Contouring the search unit wedges consistent with the scan surface of the component improves the transfer efficiency of sound energy, from the wedge to the component, by allowing the entire active region of the sound beam to be coupled to the component. This maximizes the acoustic energy propagated into the material. This coupling is essential when using phased array search units that possess a series of small elements that need to propagate energy for beam forming over the entire surface of the search unit. The allowance for no more than a 1/32 inch (0.8 mm) gap between the search unit and the component surface along the entire scan length is considered sufficient, and is consistent with the requirement mandated in qualified inspection procedures for dissimilar metal welds.

c) **Inspection Frequency**:

Attenuation associated with grain boundary interactions, grain sizes and grain orientation increases with the inspection frequency. Component thickness (and the number of potential grain boundary interactions) also increases attenuation. However, a decreased inspection frequency (and corresponding longer wavelength) decreases the potential for detecting smaller and tighter flaws and reduces the capability of resolving flaw extremities for depth sizing. Selection of inspection frequency for cast austenitic materials is therefore a compromise, as in other materials. Thinner cast austenitic materials (e.g. equal to or less than 1.6-inches thick) allow for the use of slightly higher inspection frequencies. Studies have shown typical frequencies to be in the range of 0.8 MHz to 1.5 MHz [Refs. 4.16 and 4.23], with increases up to 2.0 MHz occasionally being practical [Ref. 4.16]. Thicker cast austenitic materials (e.g. greater then 1.6-inches thick) necessitate inspection frequencies between 0.5 MHz – 1.0 MHz [Refs. 4.10, 4.14, 4.15, 4.20 and 4.22].

d) **Refracted Beam Angle**:

Generally, in highly attenuative materials, lower beam angles result in less scattering interactions. Reference 4.8 discusses a study of four heats of centrifugally cast Type

316 (CF8M) stainless steel pipe, two heats of centrifugally case Type 304 (CF8A) stainless steel pipe, and two heats of statically cast Type 304 (CF8A) stainless steel elbow material. These materials ranged in wall thicknesses from 2-1/2-inches (65 mm) to 3-3/4-inches (95 mm), where an optimum 1 MHz search unit test frequency yielded an optimum refracted longitudinal wave angle of 41° - 42°. This optimum frequency/angle combination resulted in the lowest material noise levels. Reference 4.10 demonstrated, in a blind test program involving three test operators, that a 40° refracted longitudinal wave angle (and 40° ID surface impingement beam angle) could detect 25% - 30% through-wall fatigue cracks with 100% reliability. This demonstration was conducted using fatigue cracked and non-cracked test specimens fabricated from 15 ring welds in centrifugally cast Type 304 (CF8A) stainless steel pipe. Subsequent studies using phased array ultrasonics on flawed test specimens have concentrated on the use of refracted longitudinal beam angles (and ID surface impingement beam angles) between 30° - 60° for the detection and sizing of ID surface initiated flaws [Refs. 4.15, 4.16, 4.19, 4.20 and 4.22]. Refracted longitudinal waves impinging the ID surface at angles between 40° - 50° also result in the largest coefficient of reflection for ID surface initiated flaws [Ref. 4.21]. For cast austenitic materials equal to or less than 1.6-inches thick generally the entire ID surface impingement angle range of 30° - 60° is effective. For thicker cast austenitic materials (e.g. greater than 1.6-inches), the higher ID surface impingement angles (and greater sound paths) are more impacted by the cast material microstructure; the range of effective ID surface impingement angles is reduced to 30° - 50°.

To increase the robustness of the examination for a wide range of flaws it is an accepted practice to increase the number of beam angles. This is the philosophy applied in qualified ultrasonic examination procedures for dissimilar metal welds where angles of 45° and 60° are common with some procedures applying three or more angles in the range 30° to 70°. The multiple ID surface impingement angles increase the chances of detecting tilted and skewed flaws having rough or smooth surfaces at the ID surface and at a location in the thickness of the examination volume.

Thus for cast austenitic materials equal to or less than 1.6-inches thick and greater than 1.6-inches thick, UT procedures should apply at least one beam angle that produces an ID surface impingement angle in the range of 30° - 50°. Generally ID surface impingement angles between 30° - 50° are more sensible for ID surface initiated flaws and a corner trap response detection approach. Higher angles greater than or equal to 55° are practical in obtaining direct impingement responses from deeper flaws; as such at least one beam angle is required that is greater than or equal to 55°.

e) **Search Unit Size**:

Since it is desirable to focus or narrow the sound beam within the cast austenitic material, in order to detect in-service type flaws (i.e. ID-surface initiating cracks), the focal point should occur at or near the ID surface of component. Search unit design requirements must consider that beam focusing can occur only within the near field zone of the search unit. The near field is a function of the search unit frequency, the ultrasonic wave velocity in the material, and the search unit active size or aperture. For a circular crystal, or the active length of an array, the near field can be expressed as:

$$N = D^2 f/4c$$

where N = near field length,
D = search unit active size or aperture,
f = search unit frequency, and
c = acoustic velocity.

Since the near field should be at least the sound path length (focal length) from the OD examination surface to the ID surface, where in-service type flaws will initiate, the minimum search unit active size or aperture can be expressed as:

$$D_{min} = [(N*4\ c)/f]^{1/2}$$

where N is equal to the required focal length or sound path to the ID surface of the cast austenitic material. In general, beam focusing within 6 dB of the maximum sound energy concentration (focal length) is generally valid from ½ to 2 times this distance. Thus a requirement that the focusing be within 80% to 110% of the nominal wall thickness of the cast austenitic material is conservative. This ensures that the acoustic energy is maximized at or near the ID surface.

f) **Verification of Focal Length:**

In a dual monolithic element search unit, the resultant focal length is defined by known design parameters such as element size, frequency, wedge angle, wedge squint angle, and material (wedge and examination material) acoustic velocity. As such, the fabricated search unit will generally provide the desired beam focusing results as verified on an appropriate reference block. A phased array search unit achieves the desired focal length by the same known design parameters, plus a set of focal laws that electronically manipulate each element of a phased array search unit to achieve a beam convergence at the desired sound path. These focal laws need to be verified by sound beam modeling in addition to reflector responses on an appropriate reference block.

2.3 Personnel Requirements

A key element to the success of examining cast austenitic materials is training. This has been concluded in a number of investigations [Ref. 4.10, 4.14 and 4.18]. To be effective, the training must be specific to the materials, examination methods and examination procedures to be applied. Awareness of the potential for beam splitting, beam distortion, and beam skewing will aid in selecting the appropriate test parameters and in evaluating the test results. Hands-on laboratory examination of cast austenitic material welds containing known flaws is mandatory. Such examinations increase a test operator's proficiency and provide confidence in the soundness of the test procedure for flaw detection and sizing. Non-blind access to the training specimens is necessary to allow for appropriate feedback in development of procedures, equipment, and personnel.

It is mandatory that the ultrasonic examination personnel who perform Section XI mandated inspections be qualified in accordance with IWA-2300. This includes the requirements of Section XI, Appendix VII. This level of training and experience includes a proficiency in discriminating between flaw indications and indications of geometric or metallurgical origin. As such it is reasonable that an additional 4 hours of classroom and 4 hours of hands-on laboratory examinations in the content as described above is sufficient.

2.4 Scanning Sensitivity

Analogous to the majority of Appendix VIII examination procedures, the scanning sensitivity needs to be sufficiently high to image relevant planar flaws for detection and sizing. Such planar flaws may have rough or smooth morphologies, and may be skewed and/or tilted with respect to the component's principal axes. Thus, they do not necessarily relate in amplitude or echo-dynamics to responses from machined calibration reflectors. Scanning at a material noise level of 5 – 20% full screen height is consistent with qualified inspection procedures for ferritic, wrought austenitic and dissimilar metal piping welds, and is equally practical for cast austenitic welds.

2.5 Calibration

The calibration process should be consistent with current practices, in that the key parameters such as calibrated test range, beam exit point, beam angle, beam focal sound path and reference sensitivity are established. Using calibration block material that is closely representative to the actual material to be examined will provide better information to be used in the evaluation of test results. Since statically and centrifugally cast austenitic materials generally have different grain sizes and orientations, these should be considered separate material types. Consistent with dissimilar metal welds, the calibration notches for cast austenitic materials should be larger than those defined in Table III-3430-1; notches having a through-wall depth of 10% of the thickness need to be represented as a minimum. Additional notches having larger through-wall depths are also recommended.

2.6 Component Surface Finish

The requirement of using large, low angle search units in conjunction with contoured wedges necessitates that scanning be conducted over both the base material and the weld crown in order to examine for flaws parallel and transverse to the pipe weld and to cover the required Figure IWB-2500-8 examination volume. Therefore the weld crown needs to be flush with the adjacent cast austenitic base material to allow for adequate ultrasonic coupling with the examination surface. This requirement is similar to that mandated by Appendix VIII qualified procedures for the examination of dissimilar metal welds. Ideally the gap between the search unit and the examination surface should be less than 1/32-inch (0.8 mm), as is currently specified in ASME Code Section XI, Appendix D.

2.7 Examination

Figure IWB-2500-8 defines the examination volume for pipe welds in general. As a minimum, scanning must be performed to detect flaws in the inner 1/3T of the weld and in ¼-inch (6 mm) of adjacent base material. This requires multiple scan paths to adequately interrogate the examination volume, particularly for flaws transverse to the weld. As such, a minimum distance of ½-inch (13 mm) from the weld toe onto the adjacent base materials shall be examined on multiple scan paths to meet this requirement.

The investigation reported in Reference 4.14 highlights a need to ensure adequate coupling exists under the entire contact face of the search unit during scanning. Inadequate coupling will often translate into high material noise levels being observed in the UT data, resulting in reduced flaw detection capability. The examination procedure should address adequate coupling, either through the required use of liberal amounts of couplant material, recognition of material reflectors at or near the ID surface, or by the use of couplant monitoring beam angles. A combination of these actions is also acceptable.

2.8 Flaw Detection and Sizing

The recording of suspected flaw indications, regardless of amplitude, is a requirement of Appendix III, III-4511 (a) and is consistent with the majority of Appendix VIII examination procedures. It is noted however that this approach for cast austenitic materials offers, in general, a capability to detect through-wall flaws having larger through-wall depth rather than ≥ 10% through-wall depth, as mandated by Appendix VIII for pipe welds. This capability should improve for thinner components. Reference 4.16 reported a capability of detecting 15% - 27% through-wall flaws in cast material up to 1.6-inches (41 mm) thick. References 4.10, 4.14, 4.18, 4.19 and 4.22 reported a capability of detecting flaws from approximately 20% - 50% through-wall depth in thicker materials.

Experimentation has shown that, for sizing in cast austenitic material, there needs to be a departure from the method in Appendix III, III-4520. The length of a flaw indication should be measured using a full amplitude drop method rather than 50% of the peak amplitude response. The full amplitude drop method is often used in Appendix VIII qualified procedures and has been shown in References 4.16 and 4.20 to result in flaw length RMS errors of less than 0.75-inch (19mm), when using automated phased array UT processes. The 50% of the peak amplitude response was applied in Reference 4.14, using a manual conventional UT examination procedure, and was shown to consistently undersize the flaw length in the range of 0.57-inch (14 mm) to 0.94-inch (24 mm) for statically cast austenitic stainless steel material and in the range of 0.22-inch (6 mm) to 1.36-inches (35 mm) for centrifugally cast austenitic stainless steel material; the full amplitude drop method of length sizing would have increased the measured lengths and would have reduced the undersizing error.

Although there are recognized limitations, particularly in thicker components, time-of-flight tip diffraction methods consistent with Appendix VIII qualified procedures are considered the best available depth sizing techniques to be used for cast austenitic materials. Factors such as beam redirection need to be considered in these attempts. The need to apply low frequency search units to compensate for the material effects reduces the resolution of the process. Some capability for using tip diffraction sizing is reported in References 4.16 and 4.20. These were both automated (encoded) scans that allowed for off-line analyses.

2.9 Scanning Methods (Encoded versus Manual)

In the 1970s and 1980s, flaw inspection investigations on cast austenitic material were mostly performed manually [Refs. 4.8, 4.10, 4.11, 4.12, 4.13, 4.14, 4.18], whereas those investigations since 2005 are primarily by encoded means [Refs. 4.15, 4.16, 4.19, 4.20, 4.22]. Both methods have shown promising results.

Both methods have also been applied to other complex inspection configurations such as dissimilar metal welds with equal success in the qualification process using phased array UT technologies, and with less success using conventional UT technologies. In the latter conventional UT case, flaw detection and length sizing qualification was achieved by either manual or encoded means however successful flaw through-wall sizing was only achieved by encoded means. Given that the conventional manual and encoded UT techniques are similar in terms of probe selection and flaw evaluation logic, the logical explanation for this flaw through-wall sizing difference is the inability of the UT examiners to recognize the difference between flaw indication responses and weld material/interface noise responses on an UT instrument containing only time and amplitude information for a single beam angle, i.e. a thin slice of the examination volume at any given search unit position. Manual phased array UT offers data displays that combine time and amplitude, and multiple beam angles to provide an instantaneous larger cross-section of the examination volume at a similar search unit position. For the latter case, the relative positions of flaw indication and weld material/interface noise signals within the observed cross-section can be understood and evaluated by the UT examiner. For an encoded examination, multiple two-dimensional data displays can be shown to allow the UT examiner to obtain an understanding of the relationship between all the recorded responses over the entire examination volume. The multiple beam angles associated with phased array UT methods provide substantially more information than single angle conventional UT methods.

For cast austenitic materials, flaw indication and weld material/interface responses will be combined with cast material noise responses to create a potentially more complex evaluation problem for an UT examiner. This will impact the technical performance of the inspection approach. The ability to review recorded data in an off-line environment, to compare recorded data from inspection to inspection, and to have the means of eliciting other expert opinions on the validity of the recorded data greatly enhances the choice for encoded scans. From the above arguments, the selection of scanning methods in the expected order of performance (higher to lower) is:

- Encoded scans using phased array UT
- Encoded scans using conventional UT
- Manual scans using phased array UT
- Manual scans using conventional UT

It is recognized that encoded scan methods involve added costs associated with development, equipment qualification, and field application. Access, schedule, geometry and dose rates may negate the use of encoded scanners for some welds. As such, manually applied scans consistent with the other technical requirements discussed earlier may be the only practical solution.

Therefore the selection of encoded versus manual scanning methods is a trade-off based on the technical performance achieved on test samples encompassing the weld configuration, and the examination environment.

3.0 CONCLUSIONS

These alternate examination requirements discussed in this paper offer a means to improve the reliability of ultrasonic examination of cast austenitic welds and base material, from the outer diameter surface. While these requirements will not provide results consistent with those defined for wrought austenitic welds and materials in Appendix VIII, Supplement 2, they define supplemental essential parameters to those in Appendix III that have come from a number of significant investigations involving flawed test samples, and share certain essential parameters with Appendix VIII qualified procedures.

4.0 REFERENCES

4.1 C.O. Ruud, A.A. Diaz and M.T. Anderson, *Literature Review – Grain Structure Identification and Fabrication Parameters of Cast Austenitic Stainless Steel (CASS) Piping*, PNNL-19002, Pacific Northwest National Laboratory, 2009.

4.2 D.S. Kupperman, *Development Techniques for Ultrasonic Flaw Detection and Characterization in Stainless Steel*, Argonne National Laboratory, data of publication not available.

4.3 H.U. Richter, *The Ultrasonic Testing of Austenitic Welds*, Technik , Volume 23, 1968, pp. 610-610.

4.4 D.W. Fitting, L. Adler, and K.V. Cook, *Ultrasonic Wave Propagation in Materials with Orthotropic (Orthorhombic) Symmetry with an Example of Centrifugally Cast Pipe*, ORNL-5609, Oak Ridge National Laboratory, February 1980.

4.5 M.M. Behravesh, *Inspection of PWR Cast Stainless Steel Piping*, Electric Power Research Institute, December 13, 1984.

4.6 P. Jeong and J.L. Rose, *Ultrasonic Wave Propagation Considerations for Centrifugally Cast Stainless Steel Pipe Inspection*, Proceedings of the Eighth International Conference on NDE in the Nuclear Industry, Orlando, Florida, November 17-20, 1986.

4.7 P. Ramuhalli et al, *Ultrasonic Characterization of Cast Austenitic Stainless Steel Microstructure: An Interim Study*, PNNL-19325, Pacific Northwest National Laboratory, April 2010.

4.8 E.T. Hughes (Westinghouse Electric Corporation), *The Ultrasonic Inspection of Cast Austenitic Stainless Steel for Primary Circuit Components in Westinghouse PWRs*, Proceedings of the International Nuclear Industries Fair, Basel, Switzerland, October 7-11, 1975.

4.9 M.S. Good and L.G. Van Fleet (Pacific Northwest Laboratory), *Ultrasonic Beam Profiles in Coarse Grained Materials*, Proceedings of the Eighth International Conference on NDE in the Nuclear Industry, Orlando, Florida, November 17-20, 1986.

4.10 E.R. Pade and J.F. Enrietto, *Reliability of Ultrasonic Test Method for Detecting Natural Fatigue Cracks in Centrifugally Cast Stainless Steel Pipe*, WCAP-9894, Westinghouse Electric Corporation, June 1981.

4.11 *Ultrasonic Detection and Sizing of Cracks in Cast Stainless Steel Samples: Round Robin Test – Screening Phase*, AB Statens Anläggningsprovning, May 20, 1986.

4.12 D.M. Verrill (United States Nuclear Regulatory Commission), *Carolina Power and Light / USNRC Meeting Summary*, Report No. 50-400/84-40, November 2, 1984.

4.13 Letter from K. A. Ainger (Commonwealth Edison) to Harold Denton (USNRC), *Interim Report on Ultrasonic Examination of Welds in Cast Stainless Steel Components at Byron and Braidwood Stations*, June 25, 1986.

4.14 R.D. Rishel (Westinghouse Electric Corporation), *Demonstration of Flaw Detection and Characterization Capabilities for Ultrasonic Examination of Main Coolant Loop Welds*, WCAP-11778, March 1988.

4.15 S.L. Crawford, M.T. Anderson et al, *Improvements in 500-kHz Ultrasonic Phased-Array Probe Designs for Evaluation of Thick Section Cast Austenitic Stainless Steel Piping Welds*, PNNL-20238, Pacific Northwest National Laboratory, February 2011.

4.16 M.T. Anderson, A.A. Diaz et al, *Ultrasonic Phased Array Evaluation of Thin-Wall Cast Austenitic Stainless Steel (CASS) Piping*, 3rd International Workshop: Future Directions for the Inspection of Cast Austenitic Stainless Steel Piping, January 28-29, 2011.

4.17 D. Coaster (WesDyne-TRC AB), *Low Frequency Phased Array Probe Specification for High Nickel Alloy Content and Cast Stainless Steel Inspection Applications*, R-T04-011 (Internal Report), February 20, 2004.

4.18 T.T. Taylor, *An Evaluation of Manual Ultrasonic Inspection of Cast Stainless Steel Piping*, NUREG/CR-3753 (PNL-5070), April 1984.

4.19 M.T. Anderson, S. Crawford et al, *Low Frequency Phased Array Methods for Crack Detection in Cast Austenitic Piping Components*, 6th International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurised Components, Budapest, Hungary, October 8-10, 2007.

4.20 D.S. Coaster (WesDyne-TRC AB), *Report from the Trial Phased Array Inspection of the Cast Stainless Steel Test Pieces*, R-T05-055 (Internal Report), July 17, 2005.

4.21 J. Krautkramer and H. Krautkramer, <u>Ultrasonic Testing of Materials</u>, Springer-Verlag, New York Inc., 1969.

4.22 M.T. Anderson, S. Crawford et al, *Assessment of Crack Detection in Heavy-Walled Cast Stainless Steel Piping Welds Using Advanced Low-Frequency Ultrasonic Methods*, NUREG/CR-6933, US Regulatory Commission, March 2007.

4.23 A.A. Diaz, A.D. Cinson, M.T. Anderson et al, *Assessment of Ultrasonic Phased Array Testing for Cast Austenitic Stainless Steel Pressurizer Surge Line Piping Welds and Thick Section Primary System Cast Piping Welds*, PNNL-17698, Pacific Northwest National Laboratory, July 2008 (published in ADAMS in July 2011).