ELECTRIC POWER RESEARCH INSTITUTE

Guidelines for Inspectability for New Plant Components

Design for Inspectability

1015139

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Product ID Number

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ABSTRACT

Experience with in-service inspection of nuclear reactor systems has demonstrated that component configurations and surface conditions severely limit the effectiveness of examinations performed in service. In addition, lack of valuable fabrication information increase the difficulty in discriminating between benign fabrication flaws and potential service induced flaws. These limitations include:

- Lack of physical access to the area to be examined
- Joint configuration does not allow 100% coverage of the required inspection volume
- The configuration of the joint is not consistent with the design configuration
- Manufacturing and repair documentation not available
- Manufacturing radiographs are not available

This document provides guidelines for the fabrication and design of new nuclear systems that will provide access and inspectability that will allow the application of pre-service and in-service examinations to be performed at their full capability. Fabrication and repair records along digitally archived records will provide the documentation required to prepare and execute and effective pre-service and in-service examinations.

Components entering service at the highest quality level will provide a sound basis for risk based in-service examination programs. Qualified pre-service examinations on components designed for inspection will provide a recorded basis for future in-service examinations. Failure to provide adequate examination access and surface preparation will transfer these costs to the utility for in-service examinations.

This is the first revision of this document and the intent is to make it available to knowledgeable vendor and utility personnel that have relevant experience in the various inspection processes. The desire that this document become an industry consensus document that can be used by utilities and vendors during the design and fabrication of new plants. Comments received will be resolved annually and included in future revisions of this document starting in 2008.

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1. INTRODUCTION

1.1 Future Construction

Construction of the world's first commercial nuclear power facility was initiated in 1956 in northwest England (Sellafield). The designers of that era did not have access to decades of in-service data and were forced to make assumptions concerning service life of components. For example the potential of cracking in austenitic welds due to intergranular stress corrosion cracking (IGSCC) was not fully realized. As a result many components were assumed to have a service life that equaled or exceeded the expected life duration of the plant. Therefore, specific design adaptations that permitted ease of inspection were generally not given priority resulting in designs based solely on structural/functional requirements, fabrication costs and durability.

Unlike the past, nuclear plant designers now know that many components are susceptible to in-service degradation and are required by law to be inspected periodically through-out the life of the facility. Requirements for inspectability do currently exist throughout various Code related documents. However, these requirements are very general providing limited specific information. For example, American Society of Mechanical Engineers (ASME) Boiler and Pressure vessel code Section XI provides general guidance for accessibility by stating that consideration should include "access for the Inspector, examination personnel and equipment necessary to conduct the examination". Article D-2000 provides more specific information related to surface finish and weld crown blending but does not address common conditions that occur as a result of blending that can lead to inspection problems. However, these requirements are not sufficiently specific to provide adequate inspectability during pre-service and in-service ultrasonic examinations. As a result a significant time and cost burden is placed on the plant owners during these inspections. Actions taken during construction, to provide adequate inspectability, will substantially reduce the time and cost of in-service examinations and reduce radiation exposure.

1.2 Objectives

The objective of this report is to draw from lessons learned over 40 years of plant operation and inspection to compile a guideline document that will contain recommendations and specifications that one should consider when designing a plant for inspectability. Current examination techniques can be highly effective provided that the component is designed for inspection, a minimum access is provided and the inspection area is free of obstructions. Most designers, fabricators and Code bodies do not fully realize the impact of material and surface conditions on the effectiveness of an in-service examination. Establishing a consensus on inspectability requirements during construction and installation will provide utilities with a tool to assure the adequacy of new designs and fabrication.

1.3 Process

This document will provide the technical basis for inspectability as well as draft requirements and specifications for new construction. In order for this document to contain an all-inclusive collection of information, the first revision will be circulated within the industry to collect comments from a variety of personnel including those who have designed, built, inspected and operate nuclear facilities. Reconciliation of these comments will be accomplished by a consensus of industry and utility positions, with further refinement performed as needed annually. Therefore it is important for the reader to realize that early revisions of this document may be missing significant information contained in subsequent revisions.

1.4 Components

This report will eventually address five areas of plant components. These include:

- Section XI pressure vessels and piping including limited information on vessel internals
- Steam generator examination (subsequent revisions)
- Balance of plant applications (subsequent revisions)
- Buried components (subsequent revisions)
- Vessel Internals (subsequent revisions)

The current revision is primary focused on Section XI pressure vessel and piping welds

1.5 Benefits

An anticipated benefit of this report is that it will provide a reference from which information can be reviewed that represents information learned over a 40 year period in the nuclear industry. It is critical that information based on lessons learned from the past be communicated to those responsible for future designs. Incorporating inspectability into a plants design will significantly reduce in-service inspection costs, provide faster inspection times, lower radiation exposures, provide a higher level of confidence in collected data and result in justification for longer inspection intervals thus reducing scopes of in-service examinations.

2. ULTRASONIC EXAMINATION EXPERIENCE

2.1 Service Experience and Concerns

Nuclear power is a mature industry having decades of operating experiences related to every aspect of a modern plant design. Some of this knowledge relates to known failure mechanisms of specific plant components. Access to this information allows designers to identify particular components that will require periodic inspections throughout the life of the plant. In many cases the inspectablity of the component design is not favorable resulting in a more difficult and costly examination. Ultrasonic examination is the primary inspection technique used for volumetric examination of components during in-service inspections. The equipment is portable and can be used in high traffic areas without the radiological concerns that radiography introduces.

In-service experiences over the last thirty years have included:

1. The discovery of Intergranular Stress Corrosion Cracking (IGSCC) in BWR piping systems [1][2]
2. The discovery of thermal fatigue in the inner radius area of BWR feed water and Control Rod Drive Mechanisms (CRDM) return nozzles [3]
3. The discovery of thermal fatigue at the PWR feed water to pipe weld as a result of thermal stratification [4]
4. Dissimilar metal weld cracking in both PWR and BWR piping systems [5][6]
5. Cracking in upper and lower head partial penetration welds in PWR units [7]

The components listed above are well documented and currently in the process of being mitigated, repaired or replaced. These mitigation and repair programs appear to be successful, but the cost and radiation dose required to perform these programs is high and potentially could have been avoided if the components had been designed for examination.

In addition to the above, there are still concerns related to other plant components that have the potential, if flawed, to degrade plant performance. The following topics are areas where design modification is clearly the preferred solution to avoid or minimize the possibility of problems and significant cost to the owner.

- Reactor Pressure Vessel (RPV) Embrittlement

The exposure to high energy neutron flux can lead to the embrittlement of reactor pressure vessel (RPV) material in the beltline region, effectively raising the ductile-to-brittle transition temperature of the metal to within normal operating ranges of the reactor. Since RPVs are not considered to be replaceable, any design modifications that can reduce this effect can potentially extend the operational life of a facility. It is expected that new RPVs will be fabricated with alloys much less susceptible to embrittlement. Studies have shown correlation of copper, manganese and nickel to the susceptibility to embrittlement. Other vessel design considerations such as the elimination of welds in the beltline region may reduce embrittlement concerns as well as in-service inspection requirements. Low temperature over pressurization and pressurized thermal shock will still be the most important considerations for PWR RPV integrity. Smooth clean inside surface conditions and qualified UT pre-service examinations should provide a high level of confidence in the integrity of the vessel [8]. These inspectable conditions will also allow for effective examination of these components during future in-service inspections. Good access and smooth scanning surfaces may also allow for faster, cheaper and more reliable examinations in the future.

- Accessibility to austenitic and dissimilar metal welds

The ultrasonic inspection of austenitic welds requires access to both sides of the weld due to the coarse micro-structure of the weld filler material. High frequency sound waves are not able to consistently penetrate through these welds in order to detect a flaw on a side opposite of a weld. The introduction of ASME Section XI Appendix VIII Performance Demonstration Initiative (PDI), clearly demonstrated the need for dual sided access on these types of welds in order to reliably detect flaws. Also, the removal of weld crowns greatly increases the ultrasonic coverage of the weld volume. In some instances, dual access is not possible due to the geometrical constraints imposed by the weld joint design or surrounding structures. Experience has shown that the configuration of the welds to be examined in-service will greatly affect the effectiveness of the examinations. Owners must insist that specified weld joints are accessible for qualified examinations in the two axial directions and two circumferential directions and that the configuration is ground or machined flush with adjoining base material. This flush surface condition will allow unimpeded access to the weld and heat affected zone adjacent to the weld, which are primary initiation point of service induced flaws. While current qualified dissimilar metal weld procedures exist that have been demonstrated from a single axial scan direction, their performance is dramatically enhanced if two scan directions is available.

- Thermal Fatigue Cracking

Thermal fatigue cracking is a failure mechanism that results when the applied stress on a component is cycled due to periodic variations in temperature. Typically temperature variations are created by coolant thermal stratifications that either result in component displacements or a localized cyclic loading on the exposed surface. In either case, these thermal cyclic stresses are superimposed on the normal operating stresses increasing the possibility of crack initiation over time. System designers attempt to guard against thermal stratifications. However, there is a possibility that valves may leak or that thermal shields may fail or be dislodged. There is also the possibility that the system may be operated outside of the expected operational parameters. In all cases, the likelihood of thermal fatigue cracking is minimized through design and preventive measures. Potential areas that are susceptible to potential thermal fatigue should be designed to provide adequate access to the susceptible areas.

- Inspectability of Cast Stainless Steel

Cast stainless steel is used throughout light water reactor systems in components such as valve bodies and pump casings. Cast stainless steel has been shown to suffer a loss in its fracture toughness over time when exposed to normal operating temperatures found in reactor systems (approximately 500–600°F). Although thermal aging occurs over a long period of time, it potentially could be an issue for older plants possibly requiring some level of inspection. Currently there is no qualified procedure for ultrasonic examination of cast stainless steel. Cast stainless steel is a very large grained material seriously impeding the penetration capabilities of sound waves. In most cases the most accessible surface is the outer surface. However, a combination of eddy current and ultrasonic techniques have shown promise when performed from the inside surface when it is sufficiently geometrically consistent to allow examination. As a minimum provisions should be made for examination from the inside surface at the RPV and the steam generator ends of the PWR main coolant loop if cast stainless steel elbow or piping is involved.

2.2 Inspection Experience

Ultrasonic and eddy current inspection techniques require inspection surfaces that are smooth and geometrically consistent. These techniques are applicable on flat as well as curved surfaces. In many cases search unit contouring is required to minimize any lift-off or gap that may exist between the search unit and inspection surface. Inspectability issues arise when the surface topography changes in such a manner that the search unit contour becomes ineffective. A significant change in the surface diameter, wavy surfaces created by surface grinding, tapered welds, weld crowns, weld splatter, etc., are all examples of geometrical surface inconsistencies that could degrade inspection results. Experience has shown field conditions to have some degree of limiting geometry present. In some cases the as-built condition varied significantly from the original design to make the component difficult to inspect. In other cases the original design was flawed from a NDE inspectability perspective. Examples of limiting geometries are described in Section 2.4. Other impediments to inspection include difficult access to the area, interferences with supports, insulation restrictions and high radiation levels. Such restrictions typically result in limited examinations, remote inspections or the use specialized tooling. For example the inspection of a dissimilar metal weld should be performed from both sides of the weld to achieve optimum effectiveness, but in limited cases only a single sided exam is possible due to geometric restrictions resulting in a limited examination. Changes in the design of the components for new plants should consider the access required for dual sided examination. Nozzle bosses, flanges and other components should be designed to include surfaces that extend out away from the component that will allow examination from both directions. Welding processes such as the use of narrow grove welds and other specialized welding processes that reduce the possibility of diametric shrinkage adjacent to the welds should be used. Narrow grove welds also reduce the width of the examination volume and provided better access for inspection. These welds also are generally easier to inspect ultrasonically due to the reduced amount of weld metal that the ultrasonic beam has to propagate through. From a practical stand point these welds also take less time to install.

2.3 Effectiveness and Performance Demonstrations

Round Robins demonstrated the need for improved detection and sizing in both piping and pressure vessel examinations in the late seventies and eighties. The introduction of ASME XI Appendix VIII Performance Demonstration Initiative (PDI) provided the process by which to clearly exhibit the effectiveness of a technique/procedure as well as the abilities of the analysis. The performance demonstration initiative has demonstratively improved the effectiveness of ISI techniques on components with smooth, geometrically consistent surfaces and where access is available from both sides. Figure 2-1 demonstrates the improvements in technology and personnel skill for the examination of stainless steel piping in the thickness range of 11 to 25 mm. The lowest red line is the result of a round robin conducted in the late seventies for circumferential flaws located on the same side of the weld as the search unit [9]. The upper blue line represents the performance for manual examiners qualified in accordance with the requirements of ASME XI Appendix VIII. Limitations still exists for axial flaws in austenitic piping and flaws on the opposite side of the weld (single sided examination). The examination of cast stainless steel has not yet been qualified for examination from either surface.

The PDI program has demonstrated that the following limitations still exist with regard to weld inspection. These limitations are based upon the inability of vendors to successfully qualify procedures using blind mockups containing natural flaws.

- Stainless steel welds - Stainless steel piping and components are required to be examined from both sides of the weld to achieve qualified coverage. Single sided inspection difficulties arise when attempting to detect and size flaws that are located on the opposite side of the weld. This requires the sound to travel through the weld filler material which can result in high signal attenuation and beam redirection. In addition, the surface condition of these welds do allow unimpeded access to the examination volume due to the presence of crowns, diametric shrinkage, tapers or other scanning restrictions.

- Cast stainless steel – Examination techniques for cast stainless steel have not been qualified for use from any surface. The underlying problem with this material is the large grain size associated with the micro-structure of both centrifugally cast and statically cast stainless steels. Use of typical inspection frequencies has not been successful due to signal scattering and attenuation. Development work is being performed using lower frequency, higher power techniques in conjunction with signal processing methods. Additional work on evaluating examination techniques from the inside surface has showed some promise, but there are limited configurations within the plant that allow access to the inside surface.

- Tapered surfaces – Examination of tapered welds is limited by the percentage of volumetric coverage. The geometric transition at the top and bottom of the taper creates a lift-off condition where ultrasonic data in both the axial and circumferential directions is not possible. As a result, only limited examinations are possible due to this disruption of the coverage. In all cases, individual configurations require qualification using samples that represent the specific configuration to be inspected. During the design of new plant components transitions in diameter should be moved outside of the examination area so they do not have an impact on the examination.

- Closely spaced austenitic welds – Examination of two austenitic welds that are located closely adjacent to one another has not been qualified through the PDI process. The dendritic structure of austenitic welds disrupts the propagation of ultrasonic signals. Procedures have not been qualified in the case of two adjacent welds that are located so that the ultrasonic beam is initiated in or passes through an adjacent austenitic weld. Future designs should consider this condition and adequate spacing between welds should be provided.

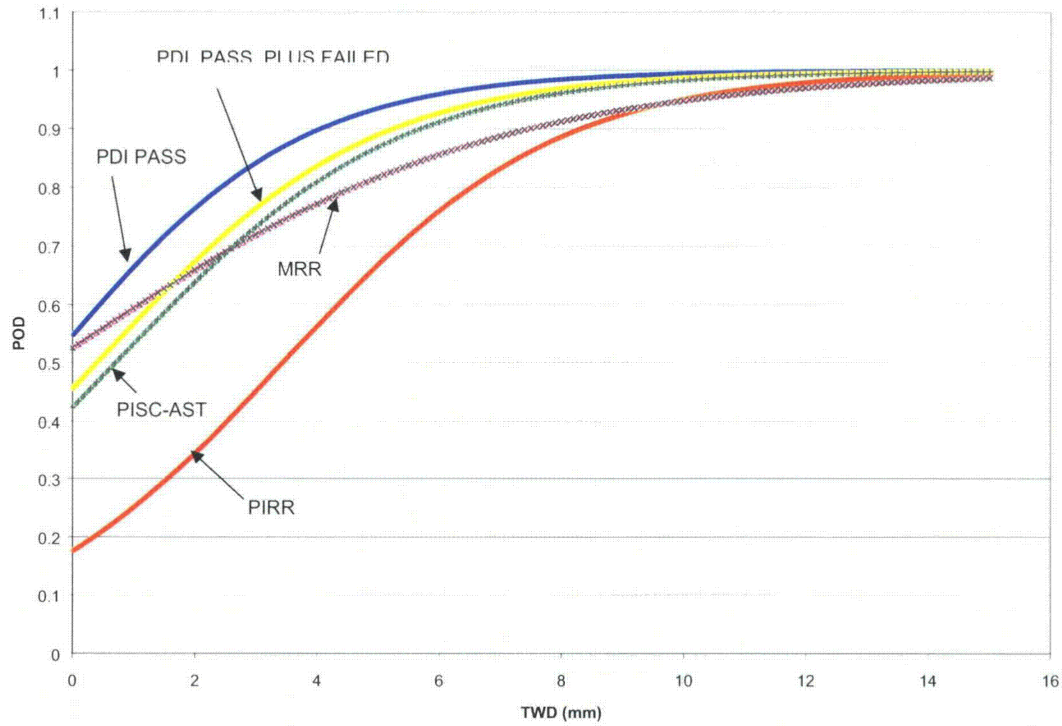


Figure 2-1
Comparison of PDI Candidate POD with that from Three Round Robin Exercises. The Material is Austenitic Piping 11 to 25 mm inches in Thickness.

2.4 Geometry Examples

This section is intended to provide the reader with examples of actual components that have geometric conditions, either by design or resulting from fabrication, that effect inspection results. These limiting configurations should be excluded from new plant designs.

Example 1

Figure 2-2 is an example of cold leg drain-to-safe-end and safe-end-to-pipe welds for a Combustion Engineering (CE) plant. This design consists of two separate welds; the DM weld and pipe weld, representing both a configuration that is fully inspectable and one that is not. The features of the DM weld (joining components 1 and 2) that make it an acceptable configuration for examination include:

- Flush (flat in the cross-sectional view) /geometrically consistent examination surface. Note this weld consists of no tapers.

- Component 1 nozzle extension provides full coverage of the weld in the down stream direction. Welds located immediately adjacent to nozzles with no extension are typically limited to a single sided examination.
- Safe-end (component 2) provides access for full examination in the upstream direction
- Weld crown removal resulting in a flush (flat cross-sectional view) weld surface provides full coverage in the circumferential direction.

If the as fabricated configuration is identical to the design configuration it would allow 100% coverage of this joint from both directions. Figure 2-3 is the axial coverage calculation on the actual configuration.

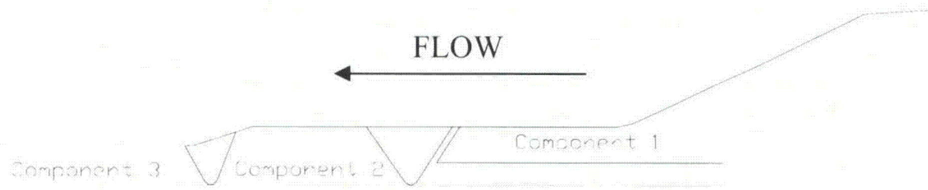


Figure 2-2
Typical CE Configuration Drawing Cold Leg Intermediate Drain Nozzle

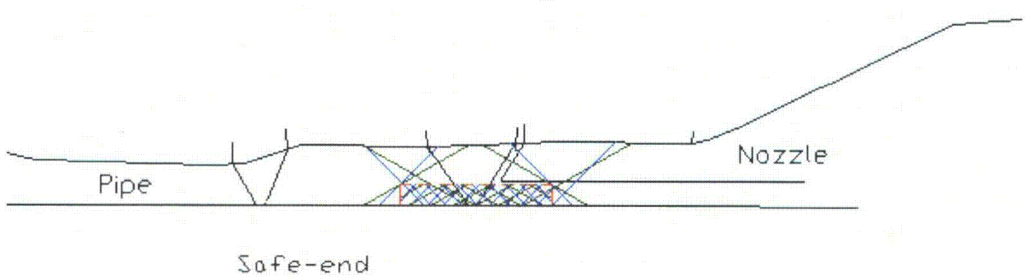


Figure 2-3
Typical CE Cold Leg Intermediate Drain Nozzle Profile and Coverage Drawings 45° and 60° RL Ax Scans

The pipe weld (between components 2 and 3) shown in Figure 2-2 is a weld located in the transition between two sections of different diameters. As a result the weld is located in a tapered section creating two fundamental issues for inspection. First, the transitions at both the top and bottom of the weld create lift-off for the search unit when scanning resulting in zones where inspection is not possible. Second, the taper angle introduces a skew to the beam like that shown in Figure 2-4 when scanning circumferentially that will limit the coverage in this direct. Special wedges can be fabricated that counter this skew effect but add cost and complexity to the exam since a separate search unit must be made for each scan direction.

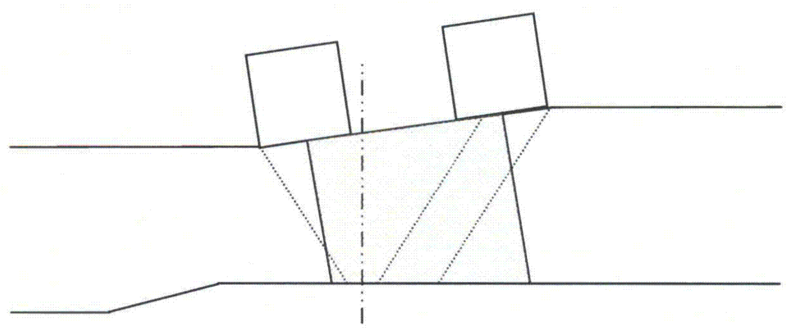


Figure 2-4
Beam skew when scanning on a tapered surface.

Example 2

The second example is a pressurizer relief nozzle and is shown in Figure 2-5. In the as-built configuration the DM weld is virtually uninspectable. This is due to the wavy surface leading to the inability to properly couple the search unit to the inspection surface. However, surface conditioning as shown by the dashed line would only provide 63% coverage of the DM weld due to the short nozzle extension present. Coverage for the pipe to safe-end weld is limited by the tapered weld. Extending the distance between the welds, adding a longer nozzle extension and maintaining a uniform thickness would greatly improve coverage for both welds.

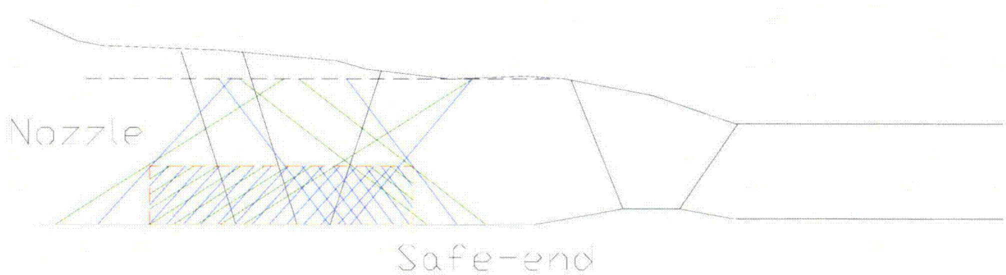


Figure 2-5

Pressurizer Safety Nozzle Profile before and after conditioning. The Coverage is based on the Combined 40° and 55° RL Scans from the Conditioned Surface.

Example 3

The design configuration for a Hot Leg drain nozzle is shown in Figure 2-6. This weld design should be inspectable since the inspection surface is smooth and sufficient area on each side of the welds is provided allowing coverage. However, the as-built configuration of this weld does not represent that shown by design drawings. A photograph of the as-built configuration is shown in Figure 2-7.

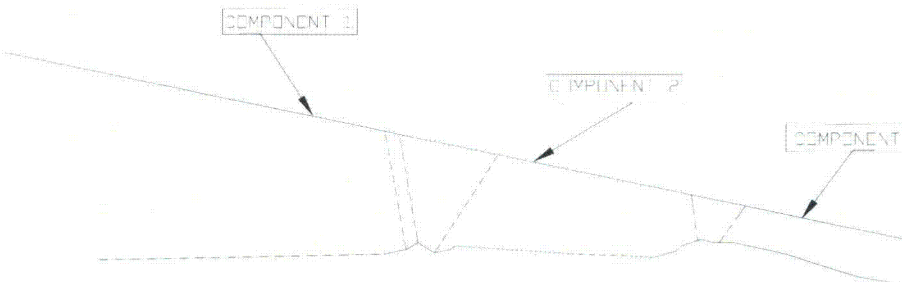


Figure 2-6
Configuration of Hot Leg Drain

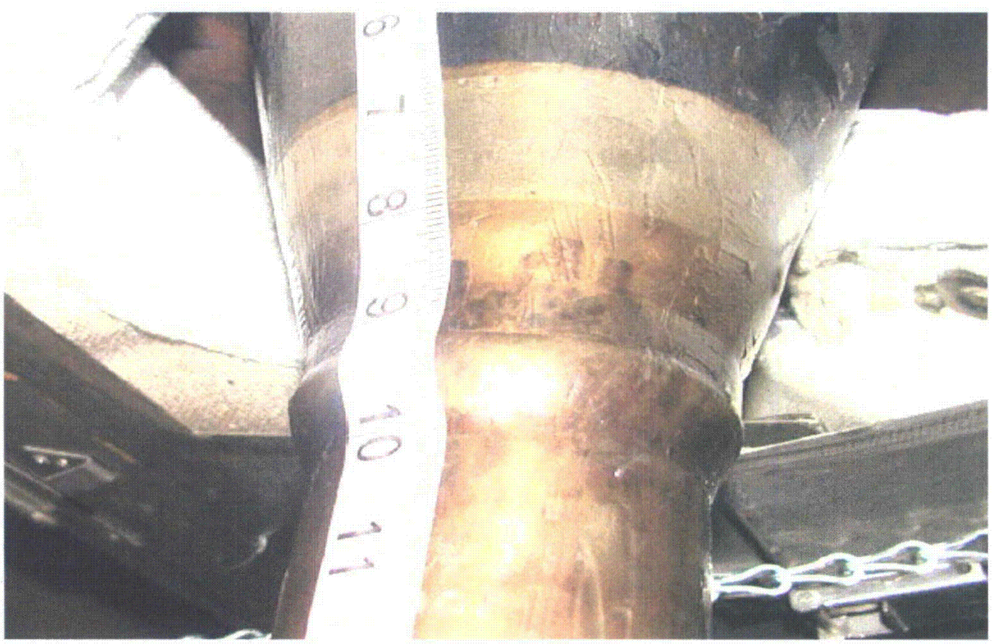


Figure 2-7
Hot Leg Drain as-built Photograph

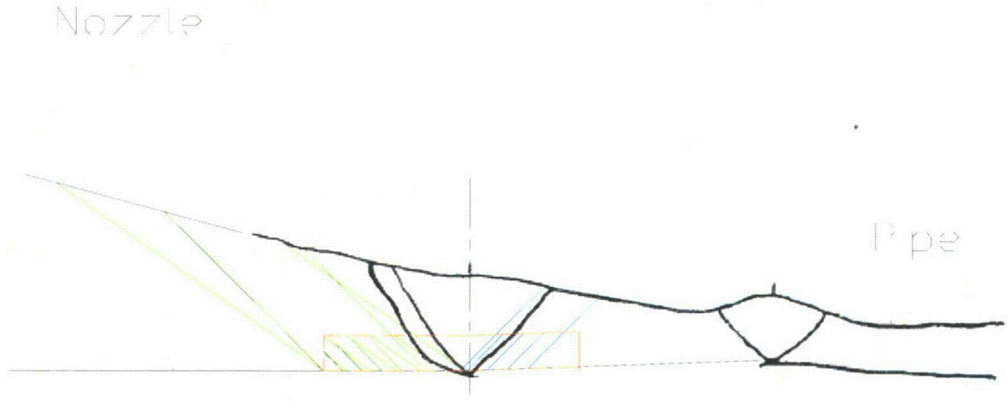


Figure 2-8
Typical CE Hot Leg Drain Nozzle Profile & Coverage Drawings

The as built configuration the DM weld surface is wavy due to grinding during weld crown removal as shown in Figure 2-8. This adverse surface condition limits coverage during scanning due to lift-off. Also the heavy crown reinforcement of the pipe weld could limit scanning preventing upstream coverage of the DM weld. Total axial scan coverage is estimated to be 33%. The profile of the pipe weld will seriously limit both axial and circumferential coverage of the pipe weld. It must be noted that even if the examination surface was completely smooth the rapid change of thickness and diameter of the design presents difficult challenges to the examination and complicates the process of selecting the proper search units for examination.

Example 4

The tapered weld found on a surge nozzle of a B&W unit is shown in Figure 2-9. This example is meant to show how axial scan coverage can be obtained using appropriate techniques. Coverage is shown for 45° beam angle from the left and 52° beam angle from the right. The changes in slope limit the ability to achieve greater coverage when using these angles. As stated previously transitions in diameters and/ thicknesses that cause tapered surfaces within the examination volume limit the effectiveness of the examination and should be avoided. While some coverage in the axial scan direction can be obtained by the adjustment of the examination angles, it is not possible to perform an adequate examination in the circumferential direction.

45°/52° RL Axial Scans

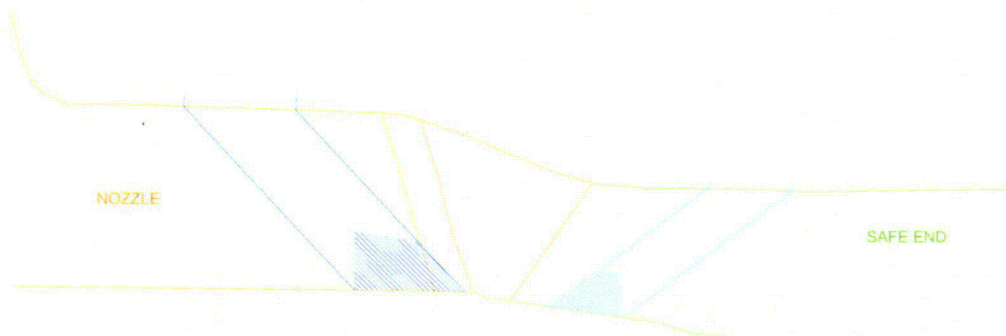


Figure 2-9
Typical B&W Surge Nozzle Profile and Coverage for 45°/52

The PDI Qualified procedure for this weld requires the use of a 60° RL search unit in combination with the 45° or 52° in at least one direction. The combined coverage including the 60° RL search unit is shown in Figure 2-10.

Combined Angles Axial Scans

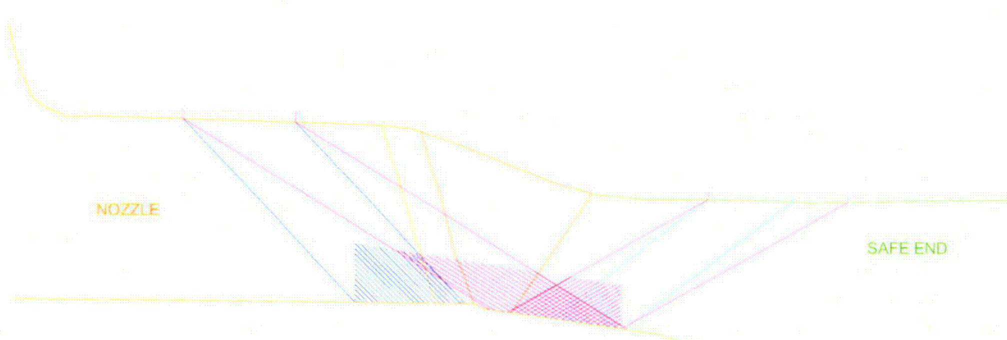


Figure 2-10
Typical B&W Surge Nozzle Profile and Coverage for Combined Angles

Example 4 Cast Stainless Steel

There are currently no qualified ultrasonic procedures for the examination of cast stainless steel from the outside surface. However, there have been some promising results from the inside surface where the geometry is sufficiently smooth to allow examination. The configuration shown in Figure 2-11 limits the examination coverage to a small portion of the pipe since sound waves are not required to propagate through the cast material and the existence of access limitations caused by the large crown reinforcement.

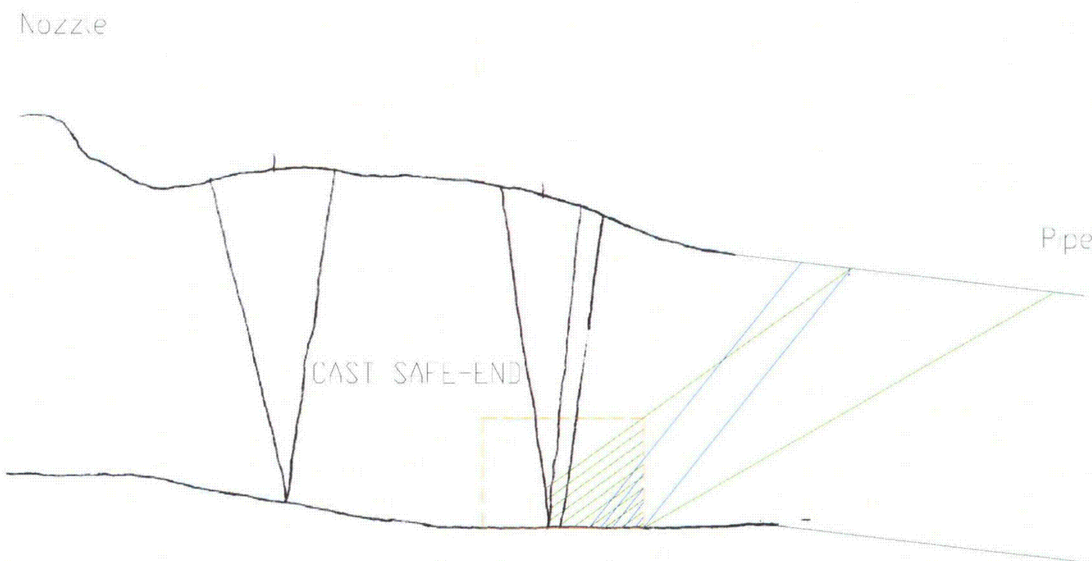


Figure 2-11
Outlet Reactor Coolant Pump Nozzle Profile & Coverage Drawings

Example 5

One of the most difficult configurations is welds that have double tapers. An example is shown in Figure 2-12. This weld has the additional restriction imposed by the adjacent weld. The axial and circumferential coverage is shown for each of the scan angles where the coverage area is shown in yellow. The lack of coverage is significant for both scan directions and is a result of:

- The short distance between the two welds.
- The short nozzle extension
- Both sides of the taper project inward and meet at the center of the weld thus causing a poor scanning surface.

Remedies for this configuration include complete the filling of the weld to a flush and smooth configuration, and extending the nozzle extension and safe-end by 2T plus 2 inches.

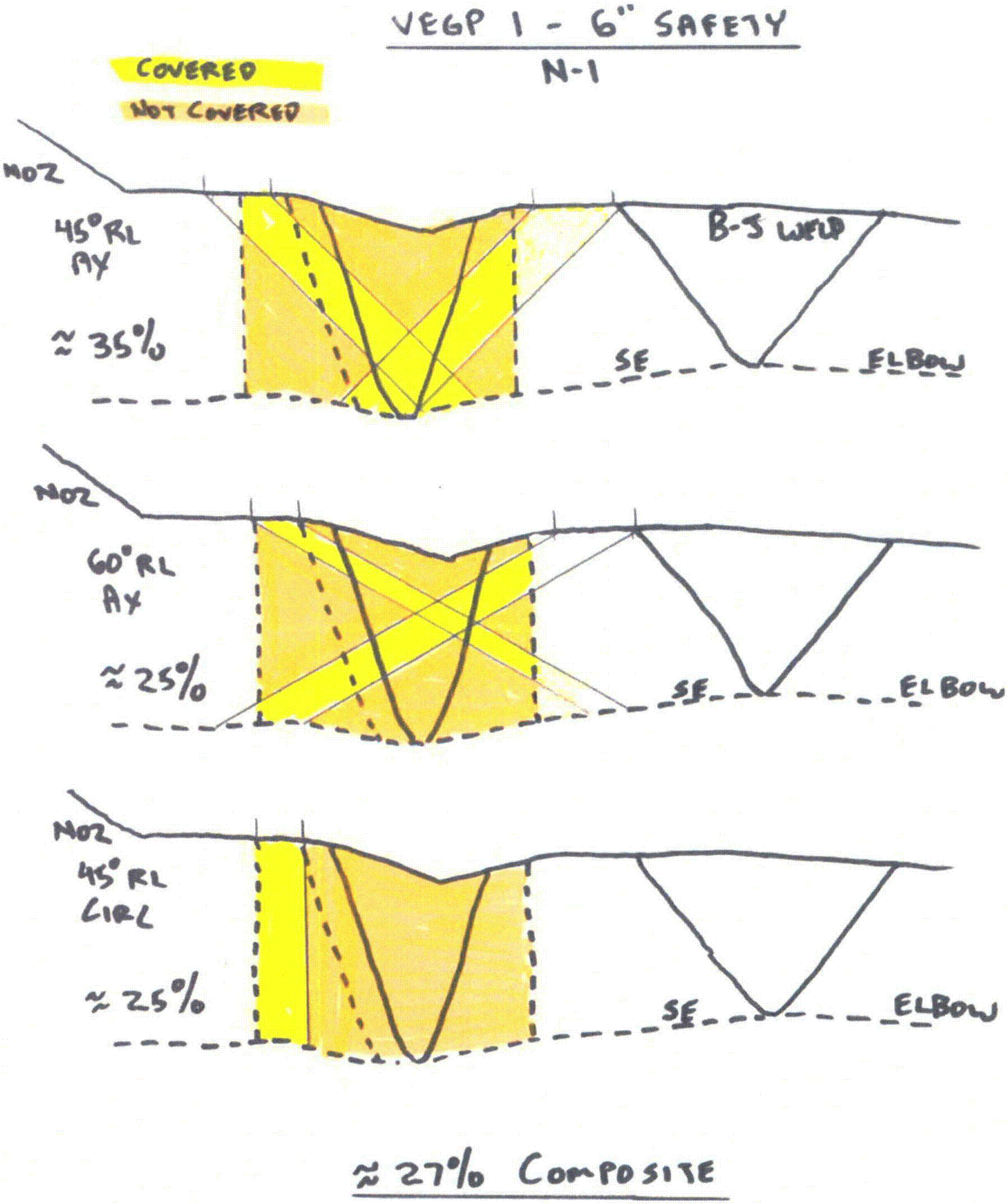


Figure 2-12
Safety/Relief Nozzle (N-1) Westinghouse Design

3. ULTRASONIC TECHNICAL BASIS

3.1 Important Factors

Many factors influence the effectiveness of ultrasonic in-service examination. The most important of these are flatness, geometrical discontinuities, access and material. Flatness (geometrical consistency) influences the quantity and coherence of ultrasound coupled into the test piece. Inside surface discontinuities such as counter bore and internal grinding produce ultrasonic signals that must be discriminated from potential defect indications. Lack of access e.g. weld crowns, elbows or tapers, block the search unit from smoothly scanning over the potential defect. The echo dynamic pattern produced by a discontinuity within the component is one of the key factors in identifying and separating it from the material noise. Material characteristics of importance include attenuation and scattering which is dependent on the crystallographic structure.

3.2 Flatness

Smoothness is the short range surface discontinuities that are small as compared to the ultrasonic wavelength e.g., grinding. Flatness is the longer range roughness e.g., welds crowns, weld beads and tapers or transitions. Both are important, however, it is the flatness which is the most difficult to address during in-service examination. Examples of flatness concerns are shown Figure 3-1. It should be noted that for this discussion, the term “flatness” should not be confused with surface curvature since ultrasonic testing can effectively be performed on components that are curved.

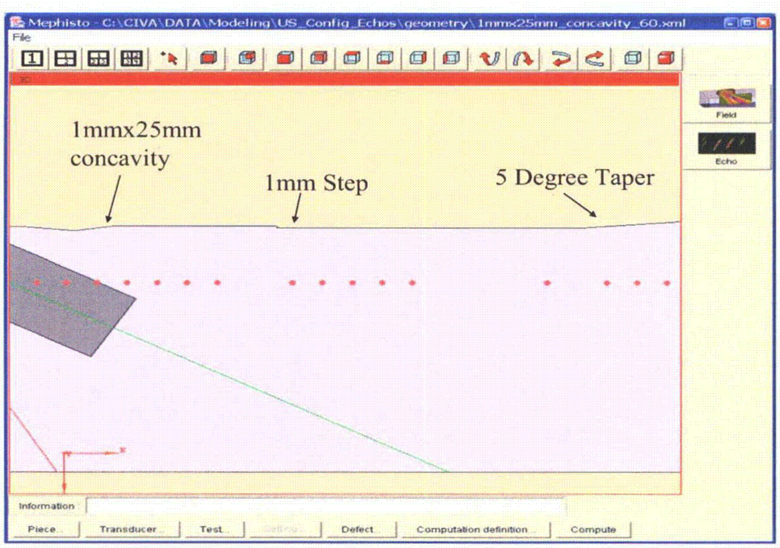


Figure 3-1
Austenitic Test Block Containing a 1-mm (0.039-in.), Concavity, 1-mm (0.039-in.) Step, and a 5° Taper

1mm x 25mm Concavity 25mm Shoe 2MHz

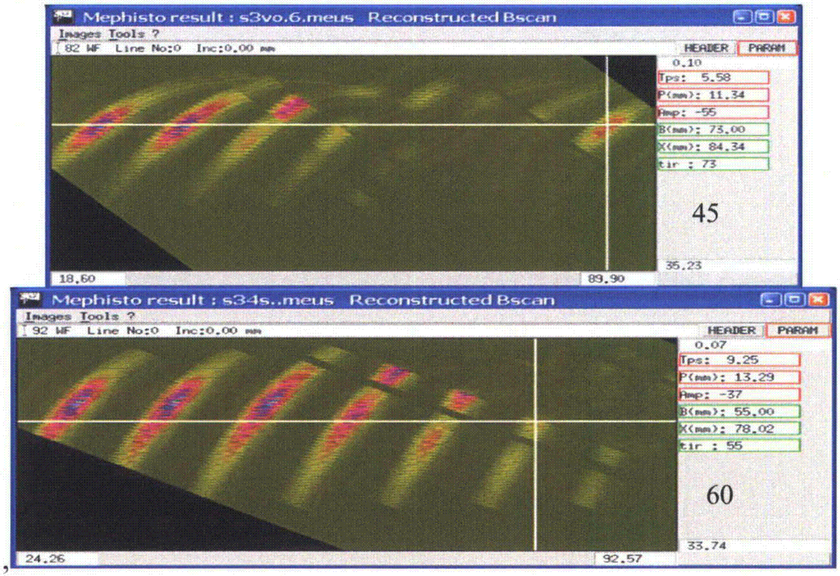


Figure 3-2
Response from SDH below the 1 × 25 mm (0.039 × 0.984 in) Concavity, 45 and 60 Angles Are Shown

Concavity 25mm Shoe 2MHz

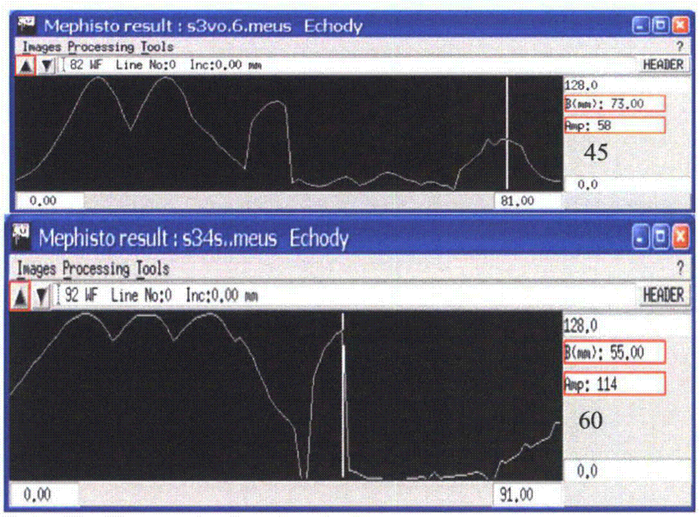
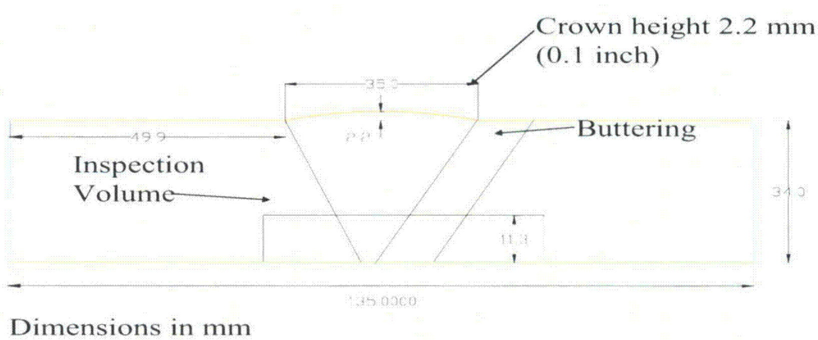


Figure 3-3
Echo Dynamic Scans Corresponding to the Image in Figure 3-2

The degree of flatness of a scanning surface may seem subjective but is based on well understood wave propagation characteristics. One may think that if the gap between the search unit bottom and the component is sufficiently small as to allow the surface tension of the couplant material to fill the void, then the sound will enter the component as required. Unfortunately this is not necessarily the case. When a couplant layer exceeds a thickness equivalent to ¼ λ (where λ is the wavelength of the sound wave in the couplant material), resonances can start to be established in the boundary layer. If present, these resonances result in conversion of sound energy to wave modes that remain in the couplant layer, thus reducing the response from a reflector. In general, the flatness of the component needs to be sufficient to maintain a very thin couplant thickness. For example, an optimum couplant layer thickness where no resonances are produced for a 2 MHz search unit using water as the couplant medium would be 0.2mm (0.008 inch). However, field conditions very rarely allow for such optimum testing conditions. As a result, some international codes typically reference a maximum allowable couplant thickness of 0.8mm (1/32 inch). It should be noted that this couplant layer thickness only applies to the area underneath the search unit where the sound exits. Also, the amount of the gap underneath a search unit is actually a function of the flatness of the inspection surface and the size of the search unit used. Search units with smaller foot prints are more adapt to scanning through wavy surfaces depending on the severity.

A profile of a weld found during in-service inspection is shown in Figure 3-4. This weld has been carefully ground and blended. The crown protrudes 2.2 mm (0.087 in.) above the plane of the pipe. This profile may not seem to be extreme. In fact, it had been described as flush during previous examinations. However it is not flush and the condition could have resulted in the crack being missed during in-service examination. Alert examiners indicated a suspect indication in an area where it appeared that the crown condition was interfering with access to the weld. The vendor requested that the surface condition of this weld be improved to eliminate the limitation. After the removal of the weld crown restriction, the examination was repeated and the vendor reported a planar-type circumferentially oriented indication contained in the weld metal. Subsequent sizing indicated that the flaw was 12.1-in. (307.3-mm) long with a through wall dimension of 0.94 in. (23.88 mm) or approximately 70% of the wall thickness.



1 mm = 0.039 in.

Figure 3-4
Weld Profile In-Service Example

The interaction between the geometry and the ultrasonic beam as the search unit is scanned over the weld profile shown in Figure 3-4 is graphically recreated in Figure 3-5. The search unit is scanned from Y = 44 to Y = 70, where Y = 0 is the left edge of the component. The search unit used in the simulation is a 45°, 2.0 MHz longitudinal wave search unit with two 10 × 18-mm (0.397 × 0.709-in.) elements. The case size is 30 × 30 mm (1.181 × 1.181 in.). Each of the wave field images is normalized to the maximum intensity contained in the data. The absolute amplitude is available in the header information for the image. The relative amplitude for each scan position is noted in dB for that image. At scan position Y = 47, there is one pixel that appears to be high amplitude and this determines the "scan gain" for that image. Otherwise, the amplitudes in the field are in line with the adjacent images. It is clear that as soon as the front edge of the shoe contacts the crown (Y = 44.5) there is a significant loss in amplitude. At scan positions greater than Y = 56, the beam has lost its coherence and most of its amplitude and is of little use for the detection of defects within the weld and buttering.

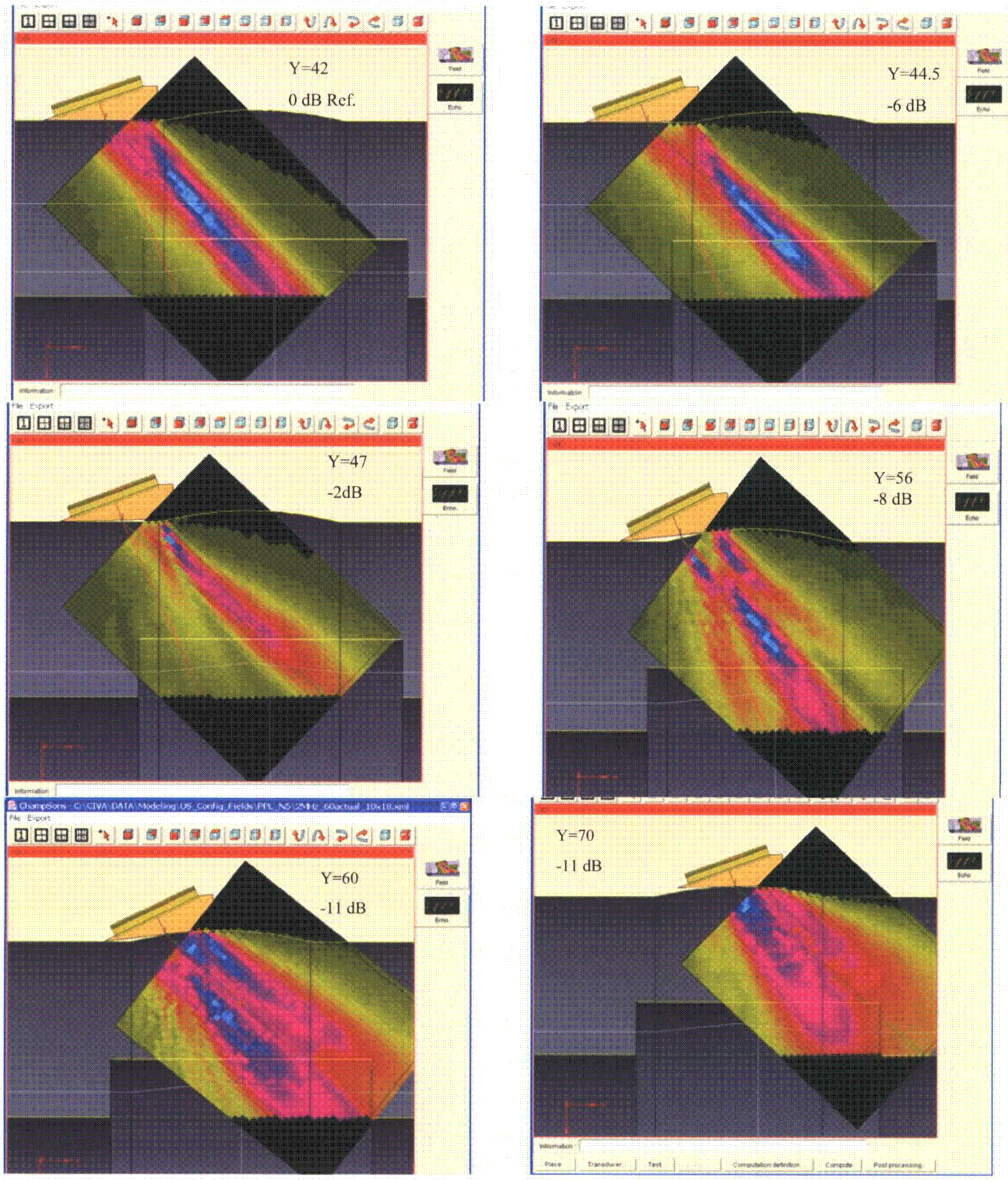


Figure 3-5
Sound Field Variations Scanning Over a Weld Crown. The Dimension "Y" Is the Position of the Search Unit. The Amplitudes Are Relative to the Reference Sensitivity in the Upper Left Corner.

If we place a series of simulated side notch reflectors at the lower surface of the component shown in Figure 3-4, it is possible to measure the coverage one might achieve on a component of this configuration. Figure 3-6 describes the layout of the reflectors relative to the weld. Each of the notches is 3.4-mm (0.134-in.) deep and 12.5-mm (0.492-in.) long and is spaced 10 mm (0.394 in.) apart. Figure 3-7 provides the B-Scan response from the left and from the right using the 60° longitudinal wave search unit. The search unit is similar to the unit used in Figure 3-5. The search unit is 2.0 MHz L-wave with two side-by-side 10 × 18-mm (0.397 × 0.709-in.) elements and the case size is 30 × 30 mm (1.181 × 1.181 in.). This is the most common size search unit used in the field for these types of examinations. This type of search unit has demonstrated good performance during the PDI testing process when the surface is prepared properly. Figure 3-8 provides the B-Scan response at 45° longitudinal wave search unit of the same size and frequency as the 60°. In both Figures 3-7 and 3-8, the cursor is placed on the fourth reflector from the left. Only the first two and last two flaws are detected with the same confidence that one would have for a flush ground crown. The middle two flaws are not adequately detected.

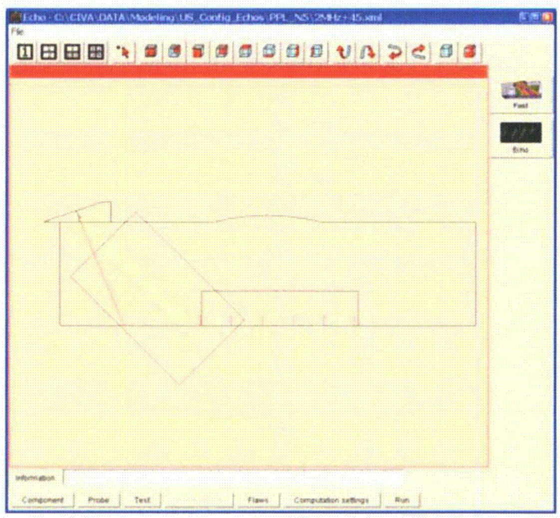
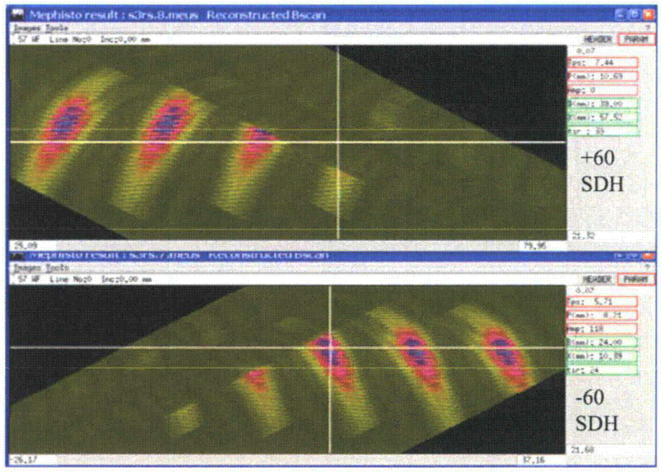
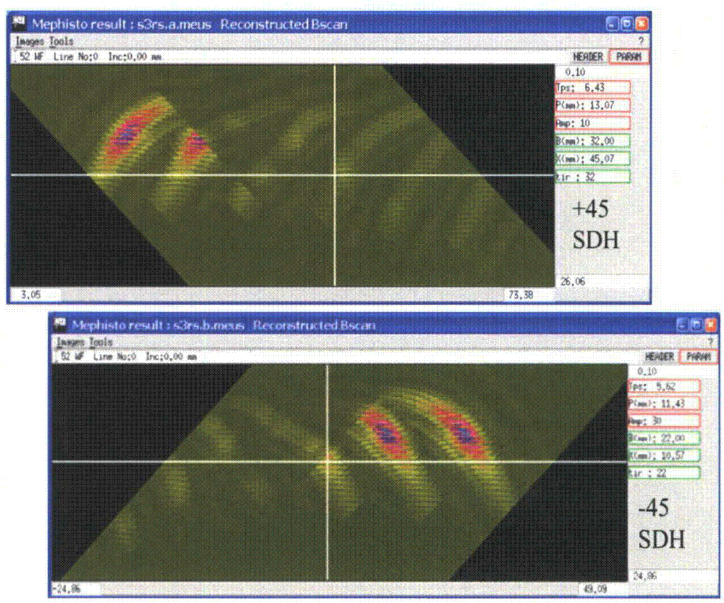


Figure 3-6
Arrangement of Notch Reflectors Relative to the Weld Shown in Figure 3-4



1 mm = 0.039 in.

Figure 3-7
B-Scan Response from the Weld Joint Shown in Figure 3-6 Using 60 Longitudinal Waves. The Component Is Scanned from the Left (+60°) and the Right (-60°).



1 mm = 0.039 in.

Figure 3-8
Calculated B-Scan Response from the Weld Joint Shown in Figure 3-6 Using 45 Longitudinal Waves. The Component Is Scanned from the Left (+45°) and the Right (-45°).

The results of this simulation show that a 70% through-wall, 12 inch long crack could have been easily missed as a result of this geometric condition.

3.3 Access

Physical access to the examination area is required. Access limitations can be in reference to many different scenarios. The most common relates to physical conditions that prevent the positioning of a search unit to locations required to achieve adequate coverage of the susceptible areas. Typically this involves the presence of an adjacent component such as an elbow or weld, surface conditions such as the presence of weld crowns or tapers, support attachments in the scan area, etc. It is important to note that during joint design and fabrication, allowance for scanning should be made on both sides of the weld. Access can also be in reference to the spatial envelope surrounding the inspection zone. Ultrasonic techniques are either applied manually or performed using automated scanning hardware. Manual inspection requires that an operator have enough access to control the search unit position using ones hand while being able to visually note its position in the area scanned. Automated systems typically require more room around the inspection area since a scanner track and associated search unit holder/gimbal assembly is involved. Designers cannot assume that manual inspections will be performed for every weld. For example, radiation dose rates may prevent a manual inspection or that qualified manual inspection techniques even exist. Currently if a flaw is detected in a dissimilar metal weld using a qualified manual technique, an automated technique must be used to determine its through-wall dimension and fully characterize the recorded flaw. During the design of new plant components access for automated systems should be required. This is especially true for vessel internals which require expensive remote tooling in order to gain access for inspection. Current reactor designs have experienced cracking and degradation of many internal components. The cost of performing these examinations is quite expensive and in many cases less than optimum. Future reactor designs should consider accessibility for inspection in their designs. Some considerations are the use of removable internal components that can easily be examined or replaced during refueling outages. Access to the vessel internal surfaces with automated inspection tools that allow effective low dose examinations of the reactor and nozzles without limitations generally experienced during present examinations. Designers should minimize the number of components inside the reactor that require inspection and design the needed components to allow easy access for inspection.

3.4 Internal Discontinuities

Discontinuities on the inside surface produce signals that are difficult to distinguish from a crack, particularly when they are close to the heat affected zone (HAZ) of the weld. Sharp counter bores and thickness transitions located close to the weld root are the primary source of these signals. In this case, the strong signal associated with an ID surface geometric reflector can mask the low amplitude signal associated with a small crack. Resolution and disposition of these indications requires unnecessary time and exposure. Discrimination of flaws from geometric signals has proven to be one the major contributors to false calls made during the qualification process. The ability to discriminate flaws from these conditions requires a very skilled examiner with many years of experience and even then the process is quite difficult. New components should assure that counter bores and other internal tapers be placed at least 2T from the weld root on either side of the weld. This would minimize discrimination problems and drastically simplify the examination.

3.5 Material

The primary effect that material has on the effectiveness of an ultrasonic examination is related to the micro-structure of that material. Coarse grained materials produce higher attenuation then fine grained materials resulting in a weaker response. Back ground noise on an ultrasonic signal that is not related to either coherent reflections or instrumentation issues, is caused by back scattering of the ultrasonic energy off the individual grain boundaries. Materials that have small grain sizes are much "quieter" than signals obtained from large grained structures. Also fine grained materials can be inspected using higher sound frequencies providing the potential for a more sensitive examination.

3.5.1 Ferritic

Ferritic materials consist of a fine grained microstructure. This small grain size results in higher signal-to-noise ratios and the compatibility for the use of higher frequency techniques (typically between 2-10 MHz). Ferritic weld filler material is also fine grained allowing for the inspection of these welds from only one side although the removal of weld crowns is required in order to obtain full coverage of the examination volume.

3.5.2 Clad Ferritic

Cladding is used to protect ferritic materials from corrosive attack. Although the cladding itself is not normally the target of an ultrasonic inspection, the sound either has to pass through the cladding to inspect the material beneath or the sound is used to interrogate the base material down to the clad layer entering through the opposite surface. The most obvious effect of cladding occurs when the sound is required to enter the component through the cladded surface. Rough and irregular cladding can result in test results that vary in sensitivity. The cladding also can redirect and distort sound that passes through the clad layer requiring a more careful analysis. When inspecting from the ferritic side of the component, care must be taken in the ultrasonic technique used to minimize clad/base metal interface reflections which can mask small interface originated flaws. Clad ferritic components in existing plants have provided very good service and to date no in-service related defects have been identified. If this material is selected for new plant construction it is recommended that the clad surface of the components be either machined smooth or welded in a fashion that provides a smooth scanning surface on the inside surface. This smooth surface helps when examinations are performed from the outside surface by minimizing the response from the clad itself, which aids in the evaluation of small indications near the clad interface.

3.5.3 Austenitic Stainless Steel

Austenitic stainless steel consists of a larger grain microstructure then ferritic steel. This generally results in the use of lower frequencies (maximum of 2.0 MHz) in order to minimize back ground noise caused by the backscatter effects and attenuation. The more serious issue associated with austenitic materials is the columnar grain structures that results from grain elongation in the direction of heat transfer during post-weld cooling. This anisotropic microstructure can redirect the sound beam in an unpredictable manner during inspection. Austenitic materials require access to both sides during weld inspection with weld crowns removed to permit access. While austenitic materials have provided good service in the existing fleet, in many cases it has shown to be susceptible to Stress Corrosion Cracking (SCC) depending on the environment it was used in. It is recommended that the use of austenitic materials be limited to systems that require its material characteristics.

3.5.4 Nickel Based Alloys and Dissimilar Metal Welds

Dissimilar metal welds and associated nickel based alloys have proven to be very difficult to inspect using ultrasonic techniques. High attenuation and sound redirection caused by large columnar grain structures are issues when testing these welds. In addition, propagation of sound through metal interfaces such as that created by the Inconel butter layer can also have deleterious effects on the sound beam. Dissimilar metal welds require access to both sides during weld inspection with weld crowns removed to permit unobstructed access to the weld and butter.

3.5.5 Cast Stainless Steel

The grain size associated with cast stainless steel can be very large. Sound attenuation is high for this material requiring the use of very low frequencies. Bean redirection also adds to the complexity of inspecting this material. To date no qualified procedure exists for the volumetric inspection of this material. While cast stainless steel has had a very good service record, the inspection problems have cost the utilities an extensive amount of money in the unsuccessful attempts to develop inspection techniques in order to effectively examine these components. This problem is being compounded as utilities start to seek life extension for their existing units. The lack of inspection techniques for cast components has made it impossible to access the condition of the older cast components. It is recommended that the use of cast stainless steel components be minimized during the design of the new plants. Materials such as clad ferritic that have good service experience and reliable examination techniques readily available should be considered.

3.6 Fabrication versus Inspection Costs

Design and manufacturing for inspectability is likely to increase the cost of fabrication although the extent of this cost can only be estimated. However, experience has shown that significant cost is associated with the pre-service and in-service inspection of components that weren't designed specifically for inspection. For example, a difficult design may lead to increased inspection times, increased dose, increased tooling costs, the use of specialize search units, the cost of highly specialized individuals, increased regulatory exposure with regards to relief requests etc., all performed with increased risk of insufficient coverage and data quality. In addition, other indirect costs can involve mockup fabrication, technique research and development costs, special technique and procedure qualifications, etc. If the initial design considers examination access the additional costs should offset by lower pre-service and in-service examinations costs.

4
RADIOGRAPHIC EXAMINATION EXPERIENCE AND FUTURE APPLICATIONS

4.1 Historical Uses

The primary use of radiography in commercial nuclear plants has been limited to the initial fabrication of the plant components and to modifications or replacement of existing components during operation. Radiography has not been the preferred method of in-service inspection in operating plants for a variety of reasons;

1) Radiological concerns are one of the primary reasons the use of radiography in operating plants has been limited. The process requires the use of high intensity radiological sources, which mandates a large exclusion or boundary be set up around the area to assure no personnel exposure. These large exclusion areas make it difficult to perform parallel work activities while radiography is in progress. These high intensity sources also cause problems for radiation protection personnel in the plant whose job is to monitor and control radiation exposure to plant personnel.

2) Many of the components do not allow access to the inside surface for the placement of the sources, which increases the exposure time required for examination and reduces resolution.

3) Background radiation from the component itself may cause premature exposure of the film and reduces the sensitivity of the examination.

4) Traditional radiographic techniques are designed to detect fabrication type defects and are less effective on detection of in-service type flaws such as Stress Corrosion Cracking (SCC).

5) If flaws are detected radiography can only provide width and length dimensions of the flaw. No depth information is possible thus making it impossible to evaluate the detected flaws to the in-service acceptance standards.

6) The intensity of the radiographic sources reduces quickly, which makes it difficult and cost intensive to use for only periodic inspections.

7) Traditional film degrades over time, which causes it to lose its sensitivity. Utilities have had to spend significant dollars to store and preserve their construction radiographs.

Recently the development of digital radiographic techniques has minimized some of these problems and has made the use of radiography more attractive to the utilities and vendors. Digital radiography employs detector plates that require no processing, allowing nearly real-time inspection. Other benefits of digital imaging include wider latitude, greater sensitivity (either reduced exposure time or energy), and digital transfer and storage of information. More recent, advancements in radiography (including high-energy portable X-ray machines, improvements in amorphous silicon technology, direct digital detectors, and improved techniques for reducing the exclusion zone) have helped to alleviate these obstacles and have made radiography a much more viable examination technique for many components.

4.2 Advanced Radiographic Techniques [11]

The most widely evaluated techniques have been concentrated on the use of phosphor plate and direct digital detectors. Descriptions of these technologies are described below.

Phosphor Plate Radiography

In the phosphor plate radiography process, the radiographic plate is coated with a phosphor compound. This compound, when exposed to gamma-rays, changes the energy level of the electron orbitals in proportion to the incident photon density, enabling the storage of a latent image.

To retrieve the image information, the plate is scanned with a laser. The light emitted by the compound when it is excited by the laser is captured by a photomultiplier and digitized. The phosphor plate image, when displayed on a computer screen, exhibits similar characteristics to conventional film. The image appears in grayscale; with the areas most exposed appearing dark gray and the least exposed light gray.
Because the phosphor compound is more sensitive to gamma-rays than is the conventional film emulsion, the phosphor plate process requires much less radiographic exposure than conventional film to achieve the same image contrast. As a result, the phosphor plate examination can be performed faster and/or with weaker radioactive sources, thereby reducing the impact of the examination on other, nearby operations. For example, a typical examination of a 10-inch (25.4-cm) diameter, schedule 40, water-filled pipe may call for a 37-curie (1.369-TBq) iridium source and, when performed in combination with a Kodak M-type film, will last approximately 25 minutes. In order to perform this examination, the radiographers will have to set an exclusion zone boundary with a radius of 330 feet (100.6 m) into which no personnel can be allowed for the duration of the radiation exposure. The same examination, when phosphor plate radiography is used, can have an exclusion zone of 50 feet (15.23 m) and duration of 3 minutes.
Advantages of the phosphor plate technique include:

- Faster exposures to achieve the same contrast
- Grayscale varying linearly with radiation exposure
- Digital archiving
- Ability to incorporate geometric measurement tools
- Ability to post-process and change contrast
- Ability to zoom

Advantages of the conventional film radiography include:
- Higher spatial resolution
- Ability of the film can be used as a material record of the examination

Direct Digital Detectors

Available direct-digital radiographic detectors are also developing and rapidly changing. The ability to perform real-time, or near real-time, radiography provides many benefits to the utility industry:
- Significant increase in examination speed since film does not have to be removed and processed
- Remote delivery of examination equipment, reducing radiation exposure to personnel
- The potential for performing examinations while the plant is on-line
- The ability to move the detector in order to obtain a better understanding of component geometry and flaw orientation
- The ability to re-align the source and detector orientation with the flaw plane to improve flaw detection
- Scanning of a component to allow compilation of three-dimensional tomographic images for defect characterization and sizing. Figure 4-2 shows a picture of a typical linear array detector.

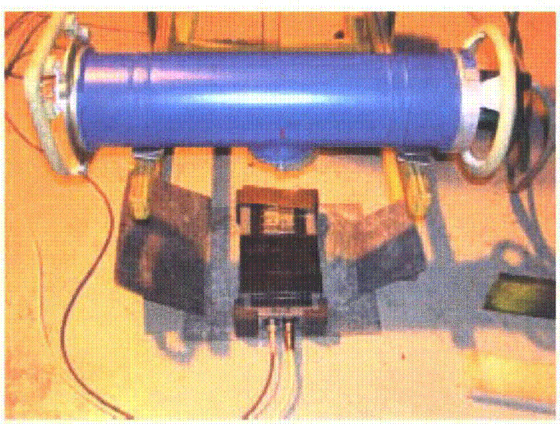


Figure 4-1
Typical Linear Array Detector

Based on current technology development in this area it is believed that digital radiography will have a big part in new plant construction inspections not only to satisfy construction codes, but also to satisfy Section XI pre-service inspection requirements for some components.

4.3 Use of Ultrasonic and Radiography for Pre-Service Examinations

Current experience with ultrasonic and radiographic techniques has shown that radiography is better suited for the detection of fabrication flaws such as slag, porosity and to lesser degree planar flaws such as cracks and lack of fusion. For this reason it not uncommon for the two techniques to produce conflicting results. There have been several instances when components that were only inspected with radiography during fabrication have had significant planar fabrication flaws detected by ultrasonic techniques at latter date. In most cases these flaws were classified as lack of fusion, which is generally orientated favorably for detection by ultrasonic techniques. Additionally, if these flaws are detected during in-service inspections they can easily be classified as service induced flaws if they are located close to the inside surface. To avoid these problems in the future it is recommended that all Class 1 and 2 components that require volumetric examination be examined both with high resolution automated ultrasonic techniques and high resolution radiographic techniques to assure all defects are detected and evaluated properly prior to the plant going on line. This dual inspection process will provide a good baseline examination for future in-service examinations regardless of what type of volumetric method is selected.

4.4 Acceptance Criteria

ASME Section III acceptance criteria are built around the detection capabilities of conventional radiography and rely on correct characterization of the flaws. Flaws that are classified as lack of fusion or cracking are rejectable regardless of their length or through-wall dimension. This stringent acceptance criterion can lead to numerous repairs. Operational experience has shown that welds with numerous repairs, especially near the inside surface are more susceptible to cracking due to the unfavorable residual stress profile that is left after the repair. In many cases it would have been better to leave the flaw in place rather than attempting repair. It is recommended that constructions codes should be revised to incorporate an acceptance standard similar to ASME Section XI (IWB-3500), which allows for evaluation of the flaw based on it size and location within the volume. This type of evaluation would allow the acceptance of flaws that are not structurally significant and reduce the number of repairs required. In order to utilize this acceptance standard depth sizing is required. Currently, the ultrasonic testing method is the only process to accurately measure the depth of flaws, but advancements in digital radiographic techniques may allow for accurate measurement of flaw height in the future.

Additionally, limits should be placed on the type and number of repairs that can be performed on a given weld before it should be cut out and replaced.

5 PROPOSED GUIDELINES FOR FABRICATION AND PRE-SERVICE EXAMINATIONS

5.1 Fabrication History and Material Records

5.1.1. Fabrication Records Retention (digital format)

Fabrication Records shall be provided in digital format for rapid retrieval in preparation and during ISI. These records should include material certifications, welding process information, as-built drawings, pictures of the weld and general area, reference mark description, etc. Records should be stored using media that is considered stable for the life of the component. Several databases are available that allow storage of electronic examination records. These databases could be modified to allow storage of all fabrication data. This would allow easy access to the complete history of the weld.

5.1.2. Repair History

All repairs made in the course of fabrication shall be documented and be provided as a part of the fabrication record. The location, through-wall extent, repair description and subsequent NDE results should be included. In-service indications often occur as a result of fabrication repairs. Many of the in-service indications have been found to be coincident with pressure vessel and piping weld repairs.

5.1.3. Digital Radiograph Storage

To the extent possible, digital radiography should be used for examination of all welds. If this is not possible, radiographs shall be digitized and stored for rapid retrieval. All radiographic records should utilize the same points of reference as other NDE inspections as well as identification markings. Enhancement of construction radiographs are valuable for the interpretations of unidentified responses found during in-service inspection. Records should be stored using media that is considered stable for the life of the component. This process will also eliminate the film deterioration problems currently be experienced with standard film radiography.

5.1.4. *Identification Marking*

All data storage files should reference a permanent identification number or code for each weld and/or component (pumps, valves, hangers).

5.1.5. *Profiling and Contour Information*

As stated in previous sections of this report, surface condition and access is extremely important and a big impact of the effectiveness of the inspection. Issues faced in the currently operating plants are lack of information available about the actual condition of the component, and the access available for examination. Most information is limited to design drawings and in some cases one single contour measurement taken in a single location around the circumference. For new plants portable laser technology is now available that can be used to address issues relative to surface contour conditions of components/configurations and provide the ability to accurately replicate these surfaces for use with NDE inspection techniques. This technology also provides the capability of cataloging all new plant component configurations, prior to the plant going into an operation cycle, to assist in future modification/inspection needs. This technology does not require the use of tracks or other mounting systems and is very portable (See Figure 4-1). Contour information as shown in Figure 4-2 can be obtained within an accuracy of 0.010 inches for 360 degree's around the component. The data is captured in a CAD based program that allows 3D viewing of the component. Thickness measurements can be added to the captured image producing a complete inside and outside profile of the component. Current ultrasonic analysis tools allow ultrasonic data to be merged into the 3D image for analysis.

In addition to the inspection benefits this information can also be used to assist in virtual training of plant components, configurations and systems. Information collected with this type of system prior to the plant going on line could be used by other plant support groups to improve human performance through virtual/simulated training, technique development for inspections and modifications. All of these uses would all have a positive impact on increasing personnel radiation safety and reducing ALARA dose rates.

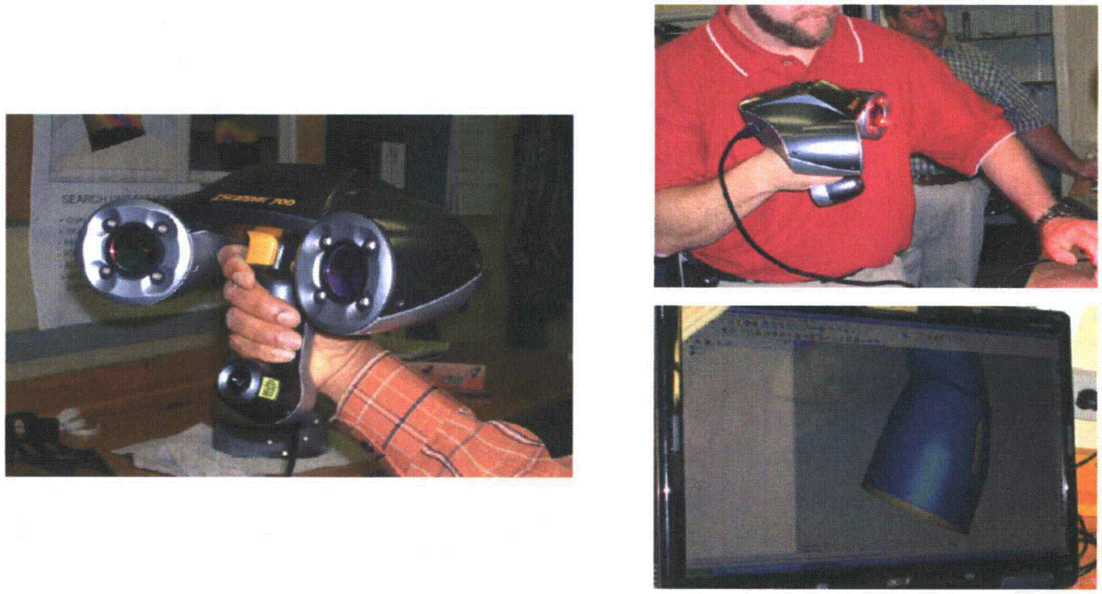


Figure 5-1
Hand Held Laser

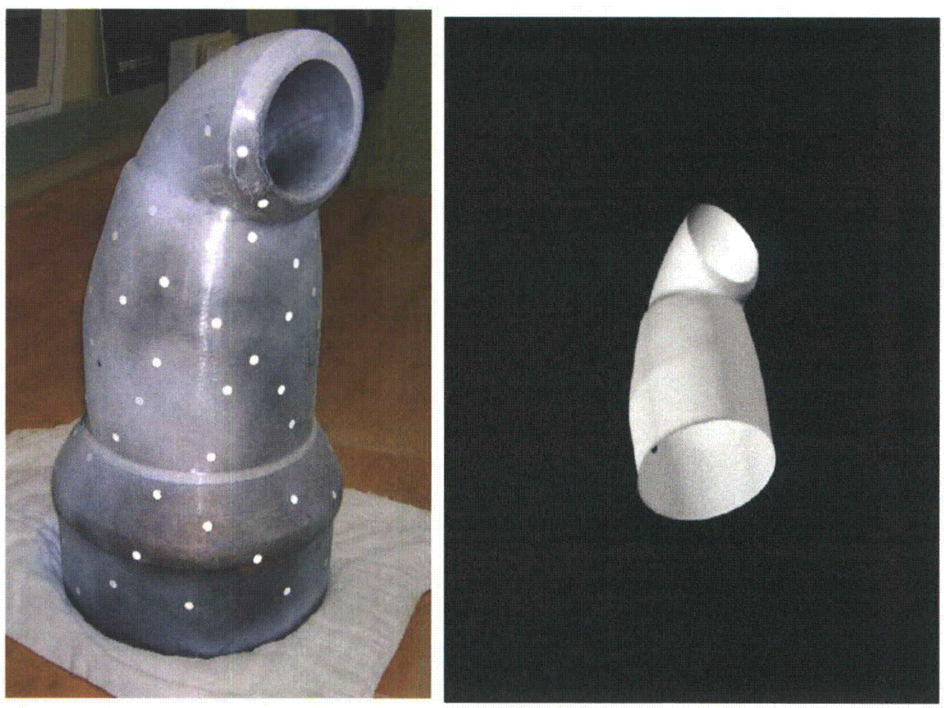


Figure 5-2
Detailed Profile Data

5.2 Imposition of Qualified Ultrasonic Examination Requirements during Fabrication.

Fabrication examinations shall be equivalent to the required qualified in-service examinations. As stated in paragraph 4.3 both radiography and ultrasonic examination techniques should be used pre-service examination of all Class 1 and 2 welds where possible.

5.2.1 Ultrasonic Examination of Repairs

At minimum, ultrasonic examinations that are equivalent to in-service examinations shall be performed on all repairs. Weld repairs often lead to clusters of small defects at fusion line of the repair. Scanning shall be performed in the direction perpendicular to the fusion line and HAZ of the repair.

5.2.2 Unnecessary Repairs

As stated in paragraph 4.4, the differences between ASME Section III and Section XI acceptance requirements can result in repairs for conditions that have little influence on the serviceability of the component. Localized variations in weld metal properties, residual stresses and geometrical conditions contribute to these locations as crack initiation sites later in the components life as well as being difficult locations for examinations. Therefore, if indications of little consequence are documented and do not interfere with the in-service examination they could be accepted without repair. As stated previously, this would require changes to the acceptance standards of ASME Section III.

5.3 Reactor Pressure Vessel

Automated examinations qualified in accordance with the requirements of ASME Section XI, Appendix VIII shall be performed for all weld examinations. These will provide a higher confidence in results of the examinations plus supply a permanent record that could be compared with in-service examinations.

5.3.1 Material / Access

- Material selection is the province of the vessel designer. It is expected that it will be resistant to radiation imbrittlement.
- Material cleanliness beyond current Code requirements is essential in assuring effective ultrasonic examination.
- Laminations and inclusions can limit the effectiveness of ultrasonic examinations and should always be the target of initial inspections.
- The use of Inconel Alloy 82/182 shall be avoided in locations exposed to reactor coolant.

- Vessel should be built out of forged rings thus avoiding vertical welds.
- RPV welds should be accessible from both the inside and outside of the vessel whenever possible.
- Grinding or machining operations that may leave surfaces in contact with reactor coolant in a sensitized condition due to cold work should be avoided.

5.3.2 Cladding

- Cladding on the internal surface of the vessel shall be flat and smooth. A flatness of 0.040 inch in 2 inches (1mm in 50mm) in areas subject to in-service inspection.
- The smoothed and flattened area shall extend a minimum of twice the material thickness on each side of the weld. The same requirement would be applicable for examination of base metal not associated with a weld, e.g., the belt line region.

5.3.3 Shell-to-Shell Welds

- Shell-to-shell welds should be examined using qualified automated examination procedures and personnel.
- It is expected that there will be no vertical welds in new PWR reactors. BWR type units may contain some vertical welds, but these can be minimized by the use of forgings.
- The main consideration for shell welds is the flatness and the cleanliness of the back-gouge area of the weld. A flatness of 0.040 inch in 2 inches (1mm in 50mm) in areas subject to in-service inspection.
- Welds should have defined reference points established that can be used for initial and in-service examinations. These reference marks should be made such that they are easily identifiable during in-service inspections.

5.3.4 Flange to Shell and Shell to Lower Head Welds

- Flange to shell and shell to lower head welds should be examined using qualified automated examination procedure and personnel. It is expected that many of the lower head welds will be eliminated in new reactor designs by using forgings rather than rolled plate for their fabrication.

- Thickness transitions at the flange-to-shell and shell-lower-head obstruct access for weld examination. Access shall be provided in at least one direction perpendicular to the weld and one direction parallel to the weld.

- Where heads contain a head-to-flange weld the weld should be prepared for automated examination. It is expected that most new reactor vessels will be fabricated using one piece forgings so this weld will be eliminated.

- Welds should have defined reference points established that can be used for initial and in-service examinations. These reference marks should be made such that they are easily identifiable during in-service inspections.

5.3.5 *Nozzles*

- Nozzle-to-shell and nozzle inner-radius regions should be examined using qualified automated examination procedures and personnel. It is expected that some of these welds will be eliminated by the use of forgings during fabrication.

- Welds should have defined reference points established that can be used for initial and in-service examinations. These reference marks should be made such that they are easily identifiable during in-service inspections.

5.3.6 *Control Rod Drive Mechanisms (CRDM) and other Penetrations*

- CRDM, Bottom Mounted Instrumentation (BMI) nozzles and other penetrations shall be examined using demonstrated procedures.

- Partial penetration welds shall be ground smooth to allow ultrasonic examination from the inside surface of the vessel. A flatness of 0.040 inch in 2 inches (1mm in 50mm) shall be provided on the weld and surrounding clad or base metal. Additional guidance in this area will be included in future revisions to this document.

5.3.7 *Internals*

- Design all vessel internal components that are subject to in-service degradation such that the susceptible areas are accessible for automated techniques. The design of removable components should be considered. These components could be easily removed and inspected during refueling outages without impact to other outage activities. If flaws are found they could then be easily replaced.

- Design all bolting for accessibility for ultrasonic and eddy current examination. Do not cover the bolt ends with anti-rotational keepers or other obstructions.
- Avoid the use of bolts that have geometrical features on the bolt head surface that could interfere with search unit seating or the introduction of sound into the component. Bolts containing stamped or raised lettering, machined divots or grooves or any protruding geometric feature should be avoided or conditioned so that subsequent inspections can be performed.
- Additional guidance in this area will be included in future revisions to this document.

5.4 Other Vessels

These vessels should be examined using Appendix VIII qualified examination procedures and personnel, as a minimum during pre-service examination. These include:

- Pressurizer
- Steam Generator Primary Side
- Steam Generator Secondary Side
- Other Vessels

Other vessels and the shell-to-flange and head-to-flange welds are currently not covered by Section XI, Appendix I or Appendix VIII. As a minimum the procedures should be qualified as in Appendix VIII and examiners should demonstrate their skill and ability to follow the procedures. Personnel qualifications on RPV, ferritic piping and austenitic welds should be an adequate demonstration. Modification of current Section XI Appendix I and VIII should be modified to include these requirements.

Qualified RPV procedures have been used in some applications. However, the outside surface longitudinal wave procedures are not optimum for non-clad vessels. Resistance to expanding the scope of Appendix I and VIII has resulted from the high cost of building additional mockups as well as procedure and personnel qualifications. A compromise position would be to qualify procedures on existing RPV and piping mockups and accept existing piping and RPV personnel qualifications for the new procedures.

5.5 Ferritic Piping and Clad Ferritic Piping

- Access shall be provided to permit full access for automated examination systems 100% coverage of the ASME Section XI examination volume for service induced flaws oriented parallel or perpendicular to the weld direction from both sides of the weld. While there are procedures qualified from one direction the reliability of two sided examinations is higher than from a single side.
- At minimum pre-service examinations should be performed where possible with a qualified automated system.
- The weld crown shall be ground flush with a flatness of less than 1/32 inch per inch for the entire scan area. See section 5.8, for piping examined from the inside surface.
- The scanning surface shall have a smoothness of 250 µinch RMS or better.
- Counter bore transitions located close to the weld root also cause spurious reflections which interfere with the detection of defects in the HAZ. A flat counter bore extending back 2T from the weld root greatly improves the effectiveness of the in-service examinations.
- Welds should have defined reference points established that can be used for initial and in-service examinations.
- When possible, perform welding in a controlled environment in an effort to minimize the number of field welds.
- Thickness transitions, tapers and supports shall be avoided within the required scan area.
- When weld repairs are required that impinge to the inside surface of the weld, consideration should be given towards replacing the entire weld since such repairs are known initiation sites for cracking.
- All weld repairs must be documented in a very detailed manor and referenced to the same reference points established for that weld.
- Advanced welding processes that are known to reduce radial shrinkage should be used when possible.
- Access ports should be designed into piping systems to permit the placement of a radiographic source inside the component if needed as long as the access port itself does not increase inspection requirements.

- The required scan area includes the surface area within two times the component thickness (t) plus 2 inches for manual examination. Additional area may be needed for automated examinations,

5.6 Austenitic Similar Metal Welds

- Access shall be provided to permit full access for automated examination systems 100% coverage of the ASME Section XI examination volume for service induced flaws oriented parallel or perpendicular to the weld direction from both sides of the weld.
- The required scan area includes the surface area within two times the component thickness (t) plus 2 inches for manual examination. Additional area may be needed for automated examinations,
- At minimum pre-service examinations should be performed where possible with a qualified automated system.
- Thickness transitions, tapers and supports shall be avoided within the required scan area.
- Automated examination will require additional area depending on the design of the scanning device.
- The weld crowns shall be removed to provide a flatness of 1/32 inch per inch over the entire scan length.
- The scanning surface shall have a smoothness of 250 μinch RMS or better.
- Counter bore transitions located close to the weld root also cause spurious reflections which interfere with the detection of defects in the HAZ. A flat counter bore extending back 2T from the weld root greatly improves the effectiveness of the in-service examinations.
- Welds should have defined reference points established that can be used for initial and in-service examinations.
- Closely spaced austenitic welds must be avoided. The effectiveness of ultrasonic examination is drastically reduced if the ultrasonic beam must pass through an austenitic weld before reaching the examination area.
- When possible, perform welding in a controlled environment in an effort to minimize the number of field welds.
- Advanced welding processes that are known to reduce radial shrinkage should be used when possible.

- Thermal or mechanical stress mitigation shall be applied to all piping welds.
- When weld repairs are required that impinge to the inside surface of the weld, consideration should be given towards replacing the entire weld since such repairs are known initiation sites for cracking.
- All weld repairs must be documented in a very detailed manor and referenced to the same reference points established for that weld.
- Access ports should be designed into piping systems to permit the placement of a radiographic source inside the component if needed as long as the access port itself does not increase inspection requirements.
- Support and stabilizing attachments should be mounted away from weld regions as not to impede scanning with manual and automated techniques.

5.7 Dissimilar Metal Welds (DMW) Examined from the Outside Surface

- The requirements for austenitic welds (5.6 above) shall apply.
- The weld crowns shall be removed to provide a flush surface with a cross sectional flatness of 1/32 inch per inch over the entire length of the scan.
- The scanning surface shall have a smoothness of 250 μinch RMS or better.
- At minimum pre-service examinations should be performed where possible with a qualified automated system.
- Thickness transitions, tapers and supports shall be avoided within the required scan area.
- The location and thickness of the buttering layer shall be identified by stamping.
- An accurate description of the weld profiles, and repair locations shall be supplied as apart of the permanent record.
- An acceptable method for profiling the welds is provided in Appendix A and is also available on the web site epri.com.
- Closely spaced austenitic welds shall be avoided.

- Configurations not included in qualified DMW procedures shall be mocked-up for qualification of the examination.
- When possible, perform welding in a controlled environment in a effort to minimize the number of field welds.
- Thermal or mechanical stress mitigation shall be applied to all piping welds.
- When weld repairs are required that impinge to the inside surface of the weld, consideration should be given towards replacing the entire weld since such repairs are known initiation sites for cracking.
- All weld repairs must be documented in a very detailed manor and referenced to the same reference points established for that weld.
- Access ports should be designed into piping systems to permit the placement of a radiographic source inside the component if needed as long as the access port itself does not increase inspection requirements.
- The required scan area includes the surface area within two times the component thickness (t) plus 2 inches for manual examination. Additional area may be needed for automated examinations,

5.8 Piping Examinations Performed from the Inside Surface

- Main coolant loop DM welds and piping welds at the RPV nozzles are performed from the inside surface for PWR reactors.
- Effective examinations of these welds require that the scan surface be machined smooth and flat (flush) in the examination area. A cross sectional flatness of 1/32 inch per inch is required.
- The scanning surface shall have a smoothness of 250 μinch RMS or better.
- Counter-bores shall be at least 2t from the weld centerline. The weld centerline shall be identified by stamping at a specified distance from the actual centerline.
- Detailed as-built dimensions shall be taken during pre-service examinations that can be used during subsequent in-service examinations. These dimensions should be referenced back to a location that can be verified remotely during ISI.
- It is possible to perform additional inside surface examinations of the reactor coolant connections from the steam generators. This may become a common examination in the future for the examination of welds associated with cast components. Dimensional information

should be obtained during construction in order to design tooling and examination plans for these types of examinations.

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5.9 Welds To Cast Austenitic Components

- Effective methods for the examination of cast austenitic components have not yet been qualified for in-service or pre-service examination, but at a minimum the same considerations defined for piping and dissimilar metal welds, should be considered for cast components.
- Ultrasonic and eddy current examinations have shown promise for examinations performed from the inside surface provided access and a good surface condition exists.

6. POTENTIAL COST SAVINGS

The basis for these guidelines is to reduce examination costs and exposure for in-service examination through the use of designs that are more compatible for inspection. These designs will increase the effectiveness and quality of inspection data and can also be used as a basis for reduced in-service inspection requirements. Effective manufacturing acceptance tests and pre-service examinations will provide components ready to enter service with inspection conditions as good as reasonably possible. The possibility of the existence of unidentified pre-service fabrication flaws should no longer be a concern thus lessoning the need for frequent inspections especially early in the components life. Below are examples of several examples of areas where proper design of components can justify reduced cost.

6.1 Longer Inspection Intervals

The effectiveness of ultrasonic examinations performed from the inside surface of the RPV have demonstrated the ability to detect and size fabrication or in-service flaws down to a size that is not a concern for vessel integrity[8]. Figure 6-1 demonstrates the effectiveness of qualified ultrasonic inside surface examinations on the postulated defect distribution of the PVRUF [10]. The PVRUF distribution was developed by NRC consultants and is based on destructive examination of five (5) different RPVs. The Post INSP lines demonstrate the impact of an Appendix VIII qualified examination will have on the postulated flaw distribution. The improvement includes both detection and sizing. This information can be used to calculate the probability of vessel failure using probabilistic fracture mechanics. The improved inspection can lower the probability of vessel failure by up to two orders of magnitude.

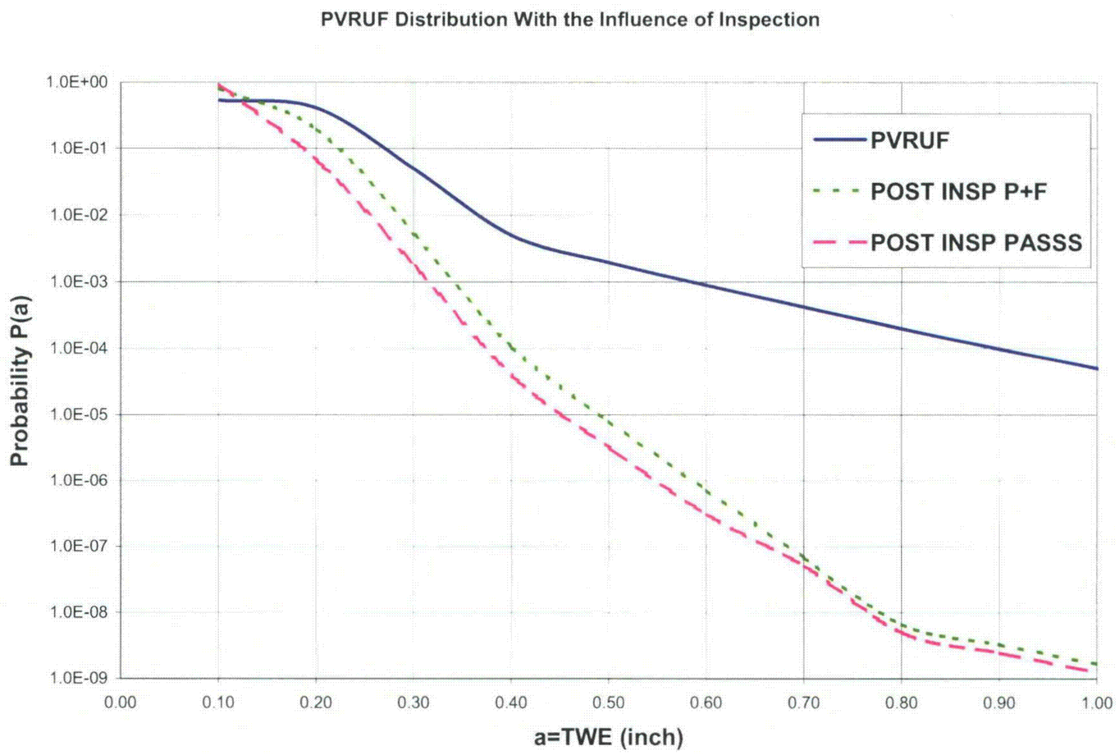

Figure 6-1
Discrete PVRUF Distribution with the Post Inspection Results for Passed and Passed Plus Failed Candidates

The improvement in examination effectiveness has been used to justify longer inspection intervals. Also, limiting the inspection volume to the inner 10% of the vessel can also be justified.

6.2 Justification for Smaller In-service Inspection Sample

Vessels and piping that have been examined using Appendix VIII qualified procedures, equipment and personnel will enter service with few undocumented flaws. Risk based inspection programs and probabilistic fracture mechanics can justify a smaller sample size and less frequent examinations.

6.3 Lower Examination Costs and Decrease impact on Critical Path

Welds that have been properly designed and properly prepared for examination before they enter service can be examined much faster than existing field conditions allow. Digitally recorded documentation packages and radiographs will simplify resolution of indications and speed the examination process. In many cases the need for special tooling and unique inspection techniques will no longer be required.

6.4 Reduced Exposure

Faster and more effective examinations provide reduced radiation exposure. Investment in fabrication and preservice examination effectiveness will reduce time, cost and exposure in service.

7. AREAS TO BE COVERED IN FUTURE REVISIONS TO THIS DOCUMENT

- Steam generator applications
- Balance of plant applications
- Buried components
- Vessel Internals

8 RECONCILIATION OF COMMENTS

Individuals and organizations are encouraged to submit comments to the document. Comments on the specific requirements proposed as well as experiences and limitations experienced during field applications are welcomed.

9 SUMMARY

The objective of this report is to draw from lessons learned over 40 years of plant operation and inspection to compile a guideline document that will contain recommendations and specifications that one should consider when designing a plant for inspectability. Non-Destructive examinations can be highly effective provided that the component is designed for inspection, a minimum of access is provided and the inspection area is free of obstructions. Most designers, fabricators and Code bodies do not fully realize the impact of material and surface conditions on the effectiveness of an in-service examination. Establishing a consensus on inspectability requirements during construction and installation will provide utilities with a tool to assure the adequacy of new designs and fabrication.

It is critical that information based on lessons learned from the past be communicated to those responsible for future designs. Incorporating inspectability into a plants design will significantly reduce in-service inspection costs, provide faster inspection times, lower radiation exposures, provide a higher level of confidence in collected data and result in justification for longer inspection intervals and reduced the work scope of in-service examinations.

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