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GERIS 2000

ULTRASONIC INSPECTION OF

FEEDWATER NOZZLES

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ABSTRACT

As a result of feedwater nozzle cracking observed in Boiling Water Reactor (BWR) plants, several design modifications were implemented to eliminate the thermal cycling that caused crack initiation. BWR. Plants with these design changes have successfully operated for over ten years without any recurrence of cracking. To provide further assurance of this, the U.S. Nuclear Regulatory Commission (NRC) issued NUREG-0619, which established periodic ultrasonic testing (UT) and liquid penetrant testing (PT) requirements. While these inspections are useful in confirming structural integrity, they are time consuming and can lead to significant radiation exposure to plant personnel. In particular, the PT requirement poses problems because it is difficult to perform the inspections with the feedwater sparger in place and leads to additional personnel exposure. Clearly an inspection program that eliminates the PT examination and still verifies the absence of surface cracking would be extremely valuable in limiting costs as well as radiation exposure. This report describes the application of advanced UT techniques to assure integrity of BWR feedwater nozzles.

The inspection methods include: 1) scanning with optimized UT techniques from the outside-vessel wall for inspection of the nozzle inner-radius regions; and 2) scanning from the nozzle-forging outside-diameter for inspection of the nozzle bore regions. Advanced methods of imaging UT data using recorded radio frequency (RF) data have been developed that show crack location, and depth of penetration into the nozzle inner surface. These techniques have been developed to the point that they are now considered a reliable alternative to the PT requirements of NUREG-0619.

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I. INTRODUCTION

Several boiling water reactor (BWR) plants experienced extensive feedwater nozzle cracking in the mid-to-late 1970's. The Nuclear Regulatory Commission (NRC) responded with NUREG 0619 (Reference 1). This NUREG discusses design modifications and establishes guidelines for periodic ultrasonic (UT) and liquid penetrant (PT) testing. Included in the design modifications were removing the cladding from the inner-radius and bore, and installing a new thermal-sleeve design. No new cracks have been observed since these modifications were incorporated.

Automated UT examinations provide a technical basis for supplanting the PT exams required by NUREG 0619. An additional advantage of automated UT is the possibility to reduce the frequency of UT examinations in the future.

The original designs of feedwater nozzles were susceptible to cracking initiated by thermal fatigue and propagated by subsequent operational temperature and pressure cycling. The crack initiation was the result of rapid temperature cycling associated with the turbulent mixing of relatively cold feedwater with hot reactor water (caused by leakage around the thermal-sleeve), coupled with the presence of stainless steel cladding on the inner surface of the low-alloy steel (LAS) nozzles. As a result of extensive evaluation (Reference 2), General Electric (GE) developed new thermal-sleeve designs with reduced leakage and recommended that the cladding be removed from the nozzle inner-radius and bore, thereby reducing the high-cycle fatigue susceptibility and improving ultrasonic inspectability. In addition, changes in sparger design, specific system modifications and changes in operational procedures were implemented to further mitigate crack initiation and growth. These system modifications have been implemented at most BWRs. The NRC notes in NUREG 0619 that these changes are responsive to the issue and are an acceptable approach to nozzle crack mitigation. To account for unexpected crack initiation, or the presence of previous indications, NUREG 0619 also requires a crack growth evaluation and periodic volumetric and surface examinations. A hypothetical flaw 0.250" depth into the base metal is used for all NUREG 0619 evaluations (Reference 3).

Removal of the cladding has the additional benefit of enhancing the ultrasonic inspectability of the nozzle inner-radius and bore. Automated-UT scanners and data-acquisition techniques now provide the means of acquiring ultrasonic data in large quantities over a relatively short period of time. These methods have been developed and tested on full-size mockups of nozzles welded to sections of the reactor pressure vessel (RPV) with the goal of determining, which combination of the parameters is best suited for crack detection and sizing. There are numerous parameters to be considered, separately and in combination, so the development and qualification program is based on extensive testing using full-scale mockups, supported by computer modeling of the nozzle geometry. This improved methodology gives reliable and quantitative measurements of crack locations and depths.

The inspection technique discussed in this document implements special methods of ultrasonic examinations of the nozzle inner-radius and bore surfaces to provide data on crack location and depth. The methods for these examinations include scanning with optimized techniques from the vessel wall, the nozzle-to-vessel-blend radius and the nozzle-forging outside-diameter (OD). Advanced methods of imaging UT data using recorded RF data show crack locations, and depths of penetration into the nozzle inner surface. The program objective is to be as quantitative as practically achievable with existing field constraints and considering personnel radiation-exposure-reduction objectives (ALARA). This inspection methodology is considered by GE to be a reliable alternative to the PT requirements of NUREG 0619.

II. ULTRASONIC INSPECTION TECHNIQUE

A. OVERVIEW

Early in-service inspections (ISI) of nuclear plants used manual UT methods and manual data-recording. This work was performed in high-radiation zones where scan time was necessarily kept to a minimum. Nozzle inner surfaces were clad and the inspection entailed complex geometries with long metal paths. These conditions, combined with the problems associated with precise positioning, reduced confidence in the examination results. These and other factors, prompted NUREG 0619, which requires periodic internal PT inspections of feedwater nozzles.

GE has developed a program using the GE Reactor Inspection System 2000 (GERIS 2000), and has significantly improved flaw detection and characterization. The UT techniques have been developed and tested on full-size Reactor Pressure Vessel (RPV) nozzle mockups of various sizes and designs. Notches and crack implants in these mockups, located in various zones along the nozzle inner-radius and bore, range in depth from 0.105" to 0.750". Figure 1 shows the various inspection zones of the nozzle inside surfaces.

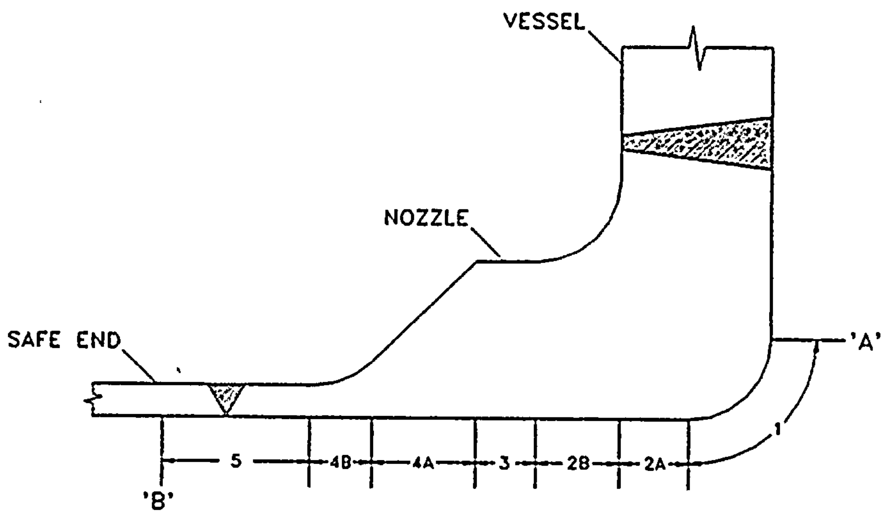

Figure 1 - Feedwater Nozzle Examination Zones

Technique development was based on extensive mock-up testing to determine which combination of parameters is best suited for flaw detection (i.e., the ability to resolve small flaw signals from noise signals). These parameters include, but are not limited to: location of the UT beam entry surface; beam and rotation angles; ultrasonic beam mode; and the angle at which the beam intersects (AOI) the flaw.

The data analysis software includes a 3-D graphics package that superimposes peak UT data points on a nozzle image. Refer to Figure 2. Data may be viewed from various orientations and magnifications. Access to digitized RF A-scan data is available for viewing any selected data point, which greatly aids in the classification and evaluation of UT data. In the A-scan display shown in the upper-right hand corner of , the amplitude (height) of the returned signal is shown on the vertical axis, and the relative time-of-flight is shown on the horizontal axis. The signal amplitude is affected by the relative orientation of the UT beam direction and the flaw aspect. The locations of the various flaws are indicated on the plan view of the nozzles, and the relative amplitude of the returns are color-coded for ease of interpretation.

Extensive mockup testing has shown that this nozzle inspection method is more effective than previous techniques, because:

- The system design provides improved signal-to-noise ratio responses and improvements in flaw detection capability;

- Enhanced data acquisition, storage and retrieval capabilities; as well as A-, B-, C-, volumetric side-view- and volumetric end-view- scan displays; and adjustable-color scales provide for quantitative data for a more reliable baseline for comparison with the results from future inspections.

With these improved techniques, GE has demonstrated increased examination accuracy and reliability on full-size nozzle mock-ups. The integrity of the feedwater nozzles can now be more thoroughly assessed by automated ultrasonic inspections.

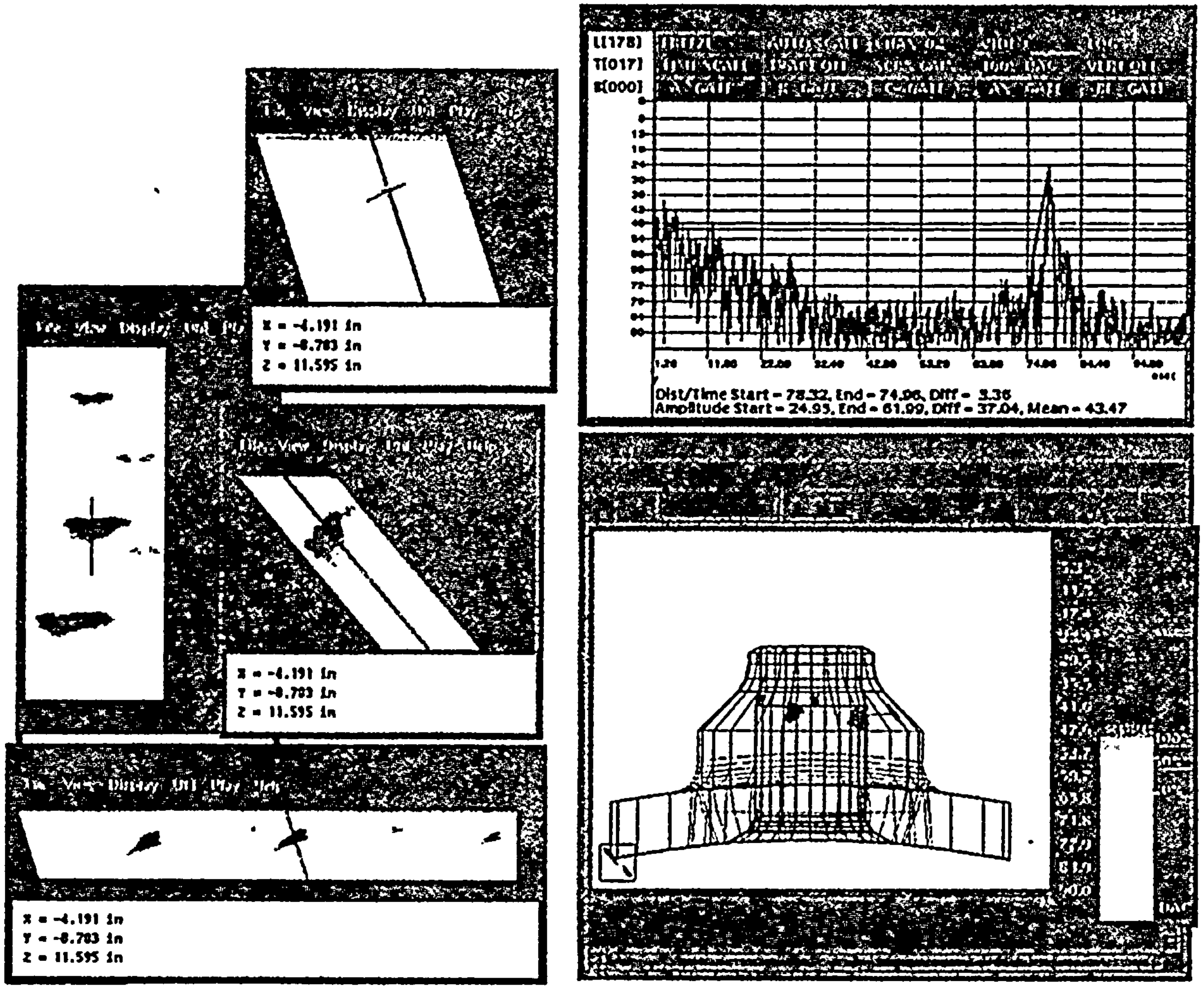

Figure 2 - GERIS 2000 Data Analysis Displays

B. GENERAL ELECTRIC REMOTE INSPECTION SYSTEM (GERIS 2000)

Referring to Figure 3, an automated scanner moves UT transducers radially and circumferentially around the outside surface of a nozzle and the adjacent surface of the RPV. The UT data is collected and stored in a digital format. The complete RF waveform is digitized and recorded on optical disks.

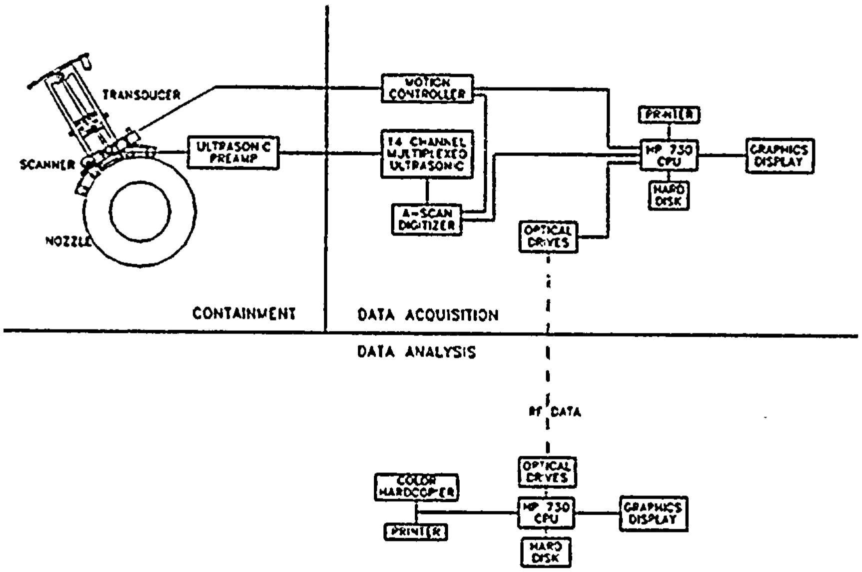

Figure 3 - GERIS 2000 Nozzle Inspection System

Nozzle-Mounted Scanner

For scanning nozzle examination Zones 1 and 2A as shown in Figure 1, the nozzle-mounted scanner (Figure 4), mounted on a channel track clamped around the nozzle OD cylindrical surface, provides the means of performing a remote ultrasonic examination. The nozzle device includes the nozzle tractor, scanner arm and transducer package.

The nozzle tractor has a main body with two motor-driven magnetic wheels and two hinged-end sections, each with one motor-driven magnetic wheel assembly. A pendulum and resolver are mounted on the main body to give the angular position of the nozzle tractor. The reciprocating scanner arm is attached to the nozzle tractor and extends perpendicular to the nozzle track for scanning the nozzle-to-vessel welds and nozzle inner-radius.

The scanner arm consists of a frame, stepping motors, a worm-gear-driven resolver, and a ball-screw-driven plate that holds the ultrasonic transducer package. The scanner arm is held to the vessel wall with two spring-loaded guide rods on the inboard end and two magnetic wheels mounted at the outboard end of the scanner arm.

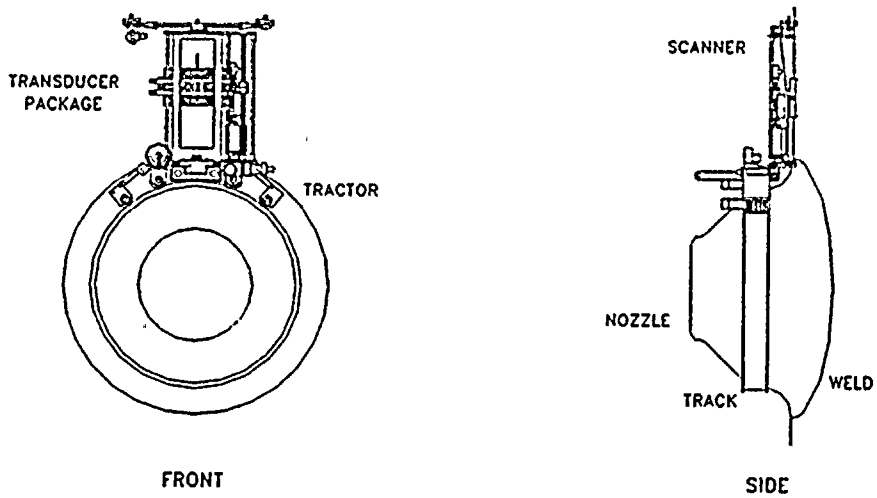

Figure 4 - Nozzle-Mounted Scanner

The transducer package consists of a combination of various transducer wedges individually mounted in a frame. The wedges produce beam angles as required by the examination technique.

Safe-End Mounted Scanner

The safe-end mounted scanner (Figure 5) attaches to a channel track clamped around the nozzle safe-end, and provides the means of performing a remote ultrasonic examination of the nozzle inner bore surface. The safe-end mounted scanner is designed for scanning nozzle examination Zones 2B, 3, 4A and 5.

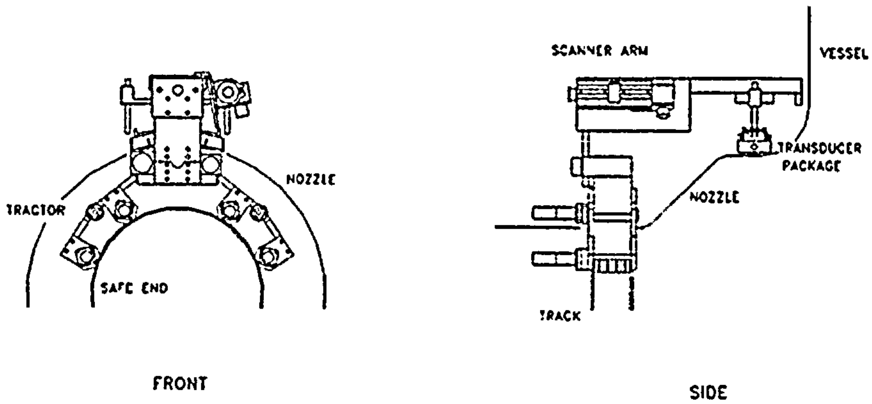

Figure 5 - Safe-End Mounted Scanner

The safe-end mounted tractor consists of a main body with two motor-driven magnetic wheels and two hinged-end sections, each with motor-driven magnetic wheel assemblies. A pendulum and resolver are mounted on the main body to give the angular position of the tractor. The reciprocating scanner arm is attached to the tractor and extends perpendicular to the safe-end track for scanning the nozzle-bore region.

C. EXAMINATION TECHNIQUES

Zone 1 Examination).

The nozzle inner-radius is examined from the vessel plate with refracted shear waves that pass through the nozzle-to-vessel weld. The sound beam is designed to intersect the inner-radius at an angle which optimizes flaw responses. Sound beam and rotation angles are dependent on the individual nozzle design.

Methods for examining the nozzle inner-radius with refracted shear waves from the nozzle OD blend radius were developed and qualified. The sound beam and rotation angles are dependent on the particular nozzle configuration.

Zone 2A Examination (Nozzle Scanner).

The Zone 2A area of the nozzle bore is examined with refracted shear waves from the surface where the nozzle OD blend radius merges with the cylindrical surface of the RPV. This scan is performed with the nozzle scanner.

Scanning from this area of the nozzle OD blend radius affords favorable conditions for flaw detection in areas where detection was once difficult. Depending on nozzle configuration, coverage generally extends from the center of the Zone 1 region well into the Zone 2B area.

Zone 2B Examination (Safe-End Scanner).

Regions of the Zone 2B area of the nozzle bore that are not examined with the Zone 2A scan are examined with refracted shear-waves from the nozzle OD cylindrical surface. The safe-end scanner is used for this examination.

Zone 3 Examination (Safe-End Scanner).

The Zone 3 area of the nozzle bore is examined refracted shear-waves from the cylindrical surface of the nozzle OD cylindrical surface. The safe-end scanner is used for this examination. The beam is directed perpendicular to the nozzle axis. The sound beam geometry is similar to that used in a circumferential piping examination.

Zone 4 Examination (Safe-End Scanner).

The Zone 4 area of the nozzle bore is examined with refracted shear-waves from the nozzle taper surface. The safe-end scanner is used for this examination.

Zone 5 Examination (Safe-End Scanner).

The Zone 5 area of the nozzle/safe-end bore is examined from the cylindrical surface of the nozzle/safe-end OD surface. The safe-end scanner is used for this examination.

D. ULTRASONIC SUBSYSTEM

The Ultrasonic subsystem has a multiplexed logarithmic UT flaw detection instrument. For each channel, the complete RF A-scan is digitized and stored on optical disks. The system stores the RF signal in logarithmic format that has an instantaneous dynamic range that is greater than 85 dB. This allows the recording of the peaks of low and high amplitude UT signals at the same time with out clipping UT signals, such as would occur with linear systems that have an instantaneous dynamic range generally less than 45 dB.

The system can record a complete set of RF waveforms from as many as 16 channels concurrently while scanning at 2.0 inches (51 mm) per second and taking data every 0.15 inches (3.8 mm). The pulse sequence for each of the channels is controlled by the Hewett Packard (HP) 730 workstation. Each channel is equipped with adjustable gate length to accommodate various types of angle-beam examination conditions. The system stores all RF data in raw form and if necessary, the data is distance-amplitude-corrected (DAC) through software and the original RF data file is never altered. The A- and C-scans are displayed during calibration and data acquisition.

E. DATA ANALYSIS

The GERIS 2000 analysis system utilizes advanced interactive color graphics to evaluate and assist in characterizing indications from service, fabrication and geometric related UT reflectors. Coordinated A-, B-, C-, volumetric side-view-, volumetric end-view- and 3D-scans are provided on a high resolution (1280 by 1024 pixels) color display. Several channels of these scans may be displayed at one time. These graphic displays have an adjustable color scale that provides the best resolution of flaw detection and characterization down to the material noise. The presentation of the data can be readily changed from color to gray scale.

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Real-time interaction between all displayed views (of a given scan) is automated and provides analysis personnel with quick coordination and identification of data.

In addition, the workstation displays peak-amplitude-UT data superimposed on a 3-D wire-frame model of the nozzle or component being examined (see Figure 2). Three-dimensional graphic tools include component viewing at any perspective or magnification. These capabilities assist in accurate UT data evaluation by analysis personnel. An on-line data base of transducer/scanner position, UT and A-scan data can be accessed during data analysis.

The real-time A-scan is readily accessible and can be viewed for data analysis. A-scan data can be viewed either statically or dynamically. Dynamic viewing enhances data evaluation by providing the echo-dynamic characteristics of recorded data.

The A-scan presentations available are RF and video. The RF presentation provides the phase of the UT signal, which can be a valuable tool for signal characterization. Additionally, the presentation can be toggled between logarithmic and linear. The logarithmic presentation provides an instantaneous dynamic range that is greater than 85 dB, and allows the viewing of the peaks of low and high amplitude UT signals at the same time.

Tip-diffraction sizing techniques are incorporated utilizing the digitized A-scan. Tip-diffraction sizing affords better accuracy in flaw depth measurements that is needed to replace the NUREG 0619 PT exams.

F. FLAW SIZING

The sizing method used is totally dependent on the tip-diffraction phenomenon -- sound energy encountering the tip of a defect will be radially scattered. This radially scattered sound returns to the transducer. Sound energy also reflects from the flaw corner and returns to the transducer. From the relationship between the time-of-arrival of the reflected signal from the flaw corner and the tip diffracted signal, and the angle of incidence of the sound energy on the flaw, the depth of the flaw can be derived.

III. ULTRASONIC TECHNIQUE QUALIFICATION PLAN

A. OVERVIEW

The ultrasonic qualification plan for the feedwater nozzle examination is based on testing full-scale mockups, (one has the clad removed). The plan incorporates a data sample set developed using ASME Code Section XI, Appendix VIII as a guideline. Appendix VIII does not presently contain specific rules for qualification of inner radius examination methods for unclad nozzles, but it was used as a guide to evaluate data, define sizing methodology and devise field inspection procedures.

The primary purpose of this demonstration was to qualify the UT equipment and techniques. Development of the full protocol for an Appendix VIII qualification is an industry effort that is on-going at the present time. Existing mockups, with flaws placed in the various inspection zones, were considered sufficient. Automated data recording and retrieval capability allowed for subsequent reviews of inspection data, as required, to confirm the validity of the detection and sizing results.

The qualification plan focused on specific portions of Appendix VIII that are applicable to the feedwater nozzle inspection. Flaw depths in the range of 0.105" to 0.750" were in the sample set, encompassing the 0.250" basis in NUREG 0619. The flaw sizing statistical measurement criteria provided by Appendix VIII was applied to the flaw samples to generate a measurement that can be compared to the actual notch depth. Since the data was automatically recorded, it is available for subsequent review and evaluation.

Appendix VIII, Supplement 5, "Qualification Requirements for Inside Radius Examinations," provides rules for extending a qualification for examination of the clad-base metal interface on the vessel (Supplement 4) to a nozzle inside radius by using a mockup containing some additional notches. Supplement 5 states that the specimens shall comply with Supplement 4, except that the flaws may be either cracks or notches. For the case of the nozzle inner-radius examination, notches are considered equally representative. However, to verify the capability of the UT techniques to detect and size actual fatigue flaws, two fatigue

cracks were implanted in the inner-radius of another nozzle mockup. The similarity between the fatigue cracks and EDM notches was demonstrated. Because this qualification plan addresses only the nozzle inner-radius, the requirements for the size and number of flaws were adopted directly from Supplement 4 of Appendix VIII.

The minimum sample set requires at least seven flaws for detection qualification, and an additional three flaws to qualify the sizing technique (i.e., a total of ten are required). While Supplement 4 allows flaws up to 0.750" in depth to be used in the sample set, the GE qualification plan for unclad nozzles had a maximum flaw depth of 0.375", a more conservative condition than required. However, qualification plan for clad nozzles had a maximum flaw depth of 0.750".

Some notches are slightly wider than nominally specified by Appendix VIII, but this is not considered detrimental to the qualification. The influence of notch width showed no significant difference in detection or sizing results for the GE technique. The notches were not filled; however, this was not expected to impact the ultrasonic examination.

The flaw configuration in the feedwater nozzle mockup had flaws in all inspection zones for the qualification data set. Flaws were radially oriented as specified in Appendix VIII, which is also in accordance with fracture mechanics predictions and field experience with nozzle cracks.

Field service personnel that perform the on-site examinations were trained and demonstrated their proficiency in the UT techniques using the samples in the clad removed feedwater nozzle mock-up. Those performing data analysis received a practical examination using recorded data, similar to that used under SNT-TC-1A qualification programs.

B. QUALIFICATION NOZZLE MOCKUPS

CLAD REMOVED FEEDWATER MOCKUP (EDM NOTCHES)

The clad removed feedwater nozzle mock-up used in the qualification testing was fabricated by GE of components from a canceled BWR manufactured under Chicago Bridge & Iron - Nuclear (CBIN) contract number 72-2505. The nozzle forging was a flanged and clad recirculation inlet nozzle with a material specification of SA 508 Class 2. The nozzle was welded into a vessel plate from shell course #1 with material specifications of SA 533 Grade B, Class 1.

The forging was machined to represent a barrel-type feedwater nozzle that had the clad removed. The scanning for Zone 2A was performed on the nozzle-to-vessel weld surface. This surface was hand welded and ground. This is typical of the nozzles that experienced nozzle-inner-radius cracking in the field. This nozzle-to-vessel weld configuration was selected because scanning from hand-ground surfaces is the most difficult.

UNCLAD FEEDWATER NOZZLE MOCKUP (FATIGUE CRACK IMPLANTS)

To confirm the detection and sizing of fatigue cracking, two fatigue crack implants were welded into an unclad feedwater nozzle forging). The unclad feedwater nozzle mockup used for implanting these fatigue cracks is from a canceled BWR. This feedwater nozzle came from a RPV that was originally fabricated by CBIN under contract number 74-C131. The nozzle forging is flanged and unclad with a material specification of SA 508 Class 2. The nozzle is welded into a vessel plate with material specifications of SA 533 Grade B, Class 1.

The fatigue cracks were generated in SA 508 Class 2 material specimens. The specimens were machined into an implant with dimensions of approximately 1.3" long by 0.38" wide by 0.49" deep with the fatigue crack in the center. Cavities were machined in the nozzle inner-radius where the cracked specimens were implanted using the gas tungsten arc (GTA) and shielded metal arc (SMA) welding processes using narrow width joint designs. The temperature of the inner-radius was maintained between 150 to 350 degrees during the implant welding process. The Post-weld heat treatment consisted of heating the inner-radius to a temperature of 1150 degrees with a soak-time of 1 hour.

CLAD FEEDWATER MOCKUP (NOTCHES AND CRACKS)

The clad feedwater nozzle mockup used for demonstrating detection and sizing is from a cancelled BWR. This feedwater nozzle came from an RPV that was originally fabricated by CE (Combustion Engineering). The nozzle forging is flanged and clad with forging material specification of SA 508 Class 2. The nozzle is welded into a plate with material specifications of SA 533 Grade B, Class 1.

The fatigue cracks in this mockup are mechanical fatigue crack implants. Cavities are machined in the nozzle inner-radius and bore where the crack is to be located. One face of the cavity is the same axis as the intended crack. A tension bar is then attached to this face using the gas tungsten arc (GTA) welding processes. A starter notch is made at the site of the fatigue crack in the base material. The tension bar is then low cycled fatigued until the tension bar separates with a section of base matherial, thus creating the crack. The other face of the implant remains in the cavity. The face of the crack is then machined from the breaker bar and positioned to match the crack face in the cavity. The crack implant is seal welded and the remaining portion of the cavity is then filled up with GTA weld material.

C. QUALIFICATION TEST RESULTS

DETECTION

As discussed earlier and shown in Figure 1, the inner-radius and bore are divided into different inspection zones. To effectively examine these zones, specially developed techniques are used where examinations are performed from the vessel plate, nozzle OD blend radius, nozzle OD and nozzle taper.

All the techniques that are presently used by GE were included in this qualification testing. Individual nozzle geometry's will determine which of the above techniques will be applied.

Comparisons between cracks and notches were made on both the clad and unclad nozzles. On the unclad nozzles, data from one EDM notch (DP1) and one fatigue crack (X21) show that the amplitude responses (dB above the noise) of comparable depths were similar.

In summary, the fatigue cracks were readily detected. This coupled with the extensive qualification with the EDM notches provides confirmation of the effectiveness of the UT system and techniques to detect fatigue cracking in the field.

SIZING

Sizing capabilities are qualified with the GERIS 2000 using the methodology of Appendix VIII. The sizing acceptance criteria outlined in Appendix VIII is demonstrated.

In summary, the EDM notches and the fatigue crack implants were successfully sized. The sizing results were acceptable to Appendix VIII acceptance criteria, therefore the UT techniques are fully validated for crack sizing in the field.

IV. CONCLUSIONS

The qualification program implemented by GE successfully demonstrated the GERIS 2000's detection and sizing capabilities . Qualification was performed on EDM notches and fatigue crack implants in full-scale mockups. The sizing results satisified Appendix VIII acceptance criteria.

In addition, depth sizing capabilities were successfully demonstrated in *"a blind test manner"* to the NRC and EPRI on the cracks in the GE clad feedwater mockup.

GE nozzle examination techniques developed over the past few years provide the means of performing dependable routine quantitative inspections. These techniques have been developed and successfully demonstrated to be a reliable alternative to the PT requirements of NUREG-0619.

□

V. REFERENCES

1) NUREG 0619, "BWR Feedwater Nozzle and Control Rod Drive Return Line Nozzle Cracking", November 1980.

2) NEDE-21821 Class III, "Boiling Water Reactor Feedwater Nozzle/Sparger Final Report", GE Nuclear Energy, March 1978.

3) Generic NRC letter 81-11 to all Power Reactor Licensees from Darrell Eisenhut, February 28, 1981.