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Class I

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 volummetric 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. The improved methodology gives reliable and quantitative measurements of crack locations and depths.

This inspection technique 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) and 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.

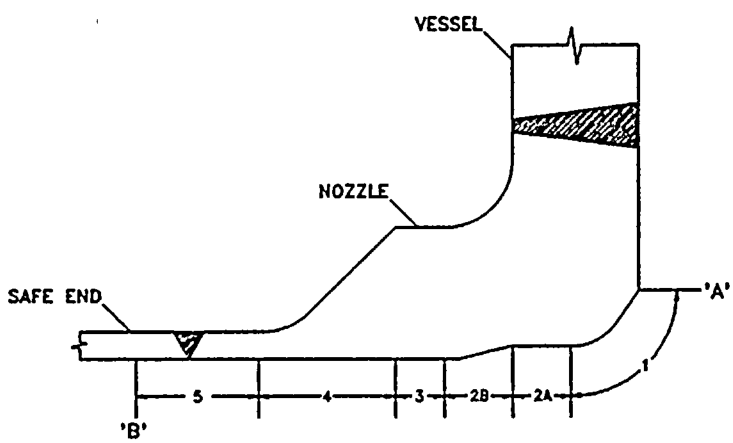

Figure 1
Feedwater Nozzle Examination Zones

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 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 Figure 2, 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-, volummetric side-view- and volummetric end-view- scan displays; and adjustable-color scales provide for quantity 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 automatic ultrasonic inspections.

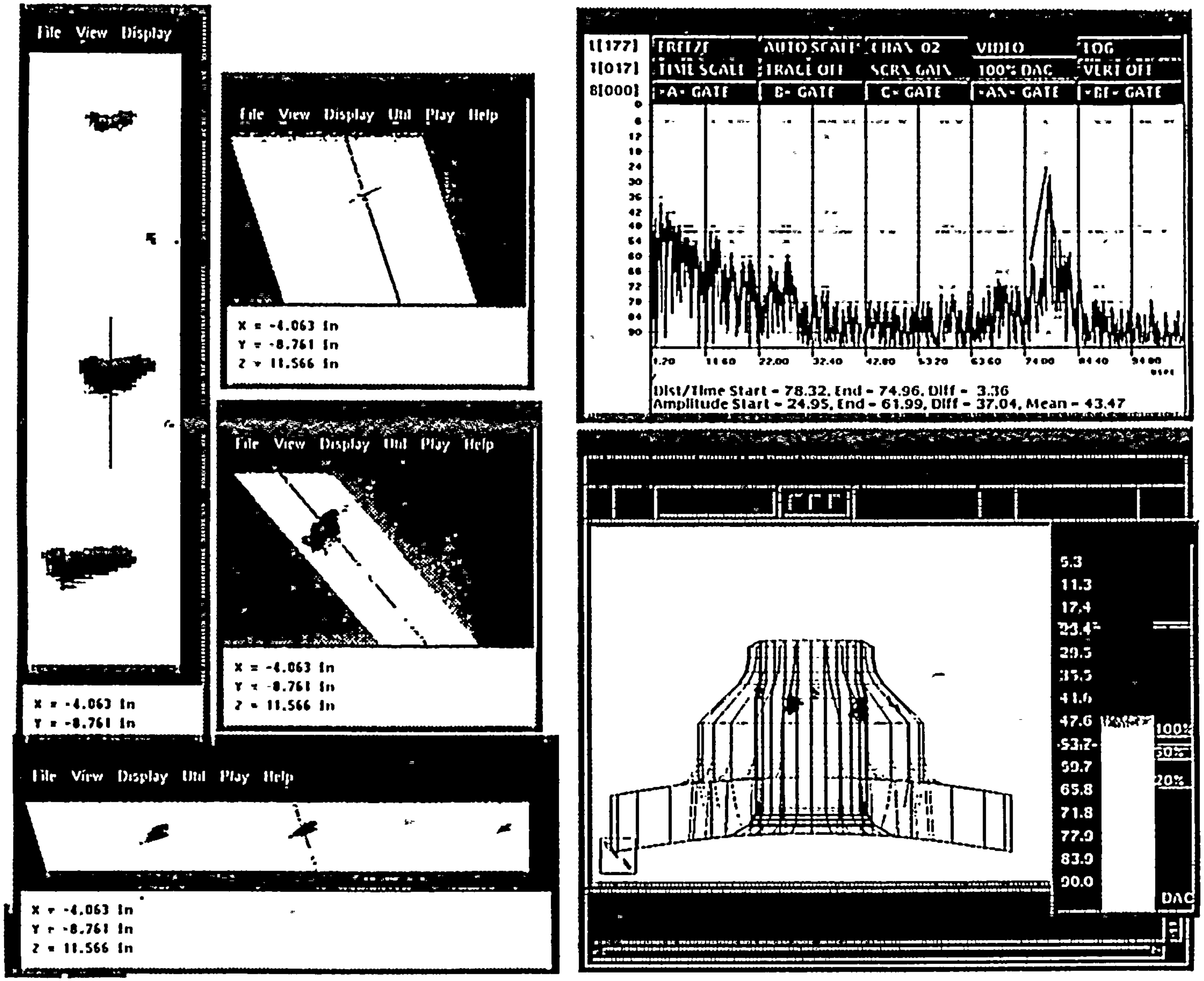

Figure 2. GERIS Data Analysis Displays

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.

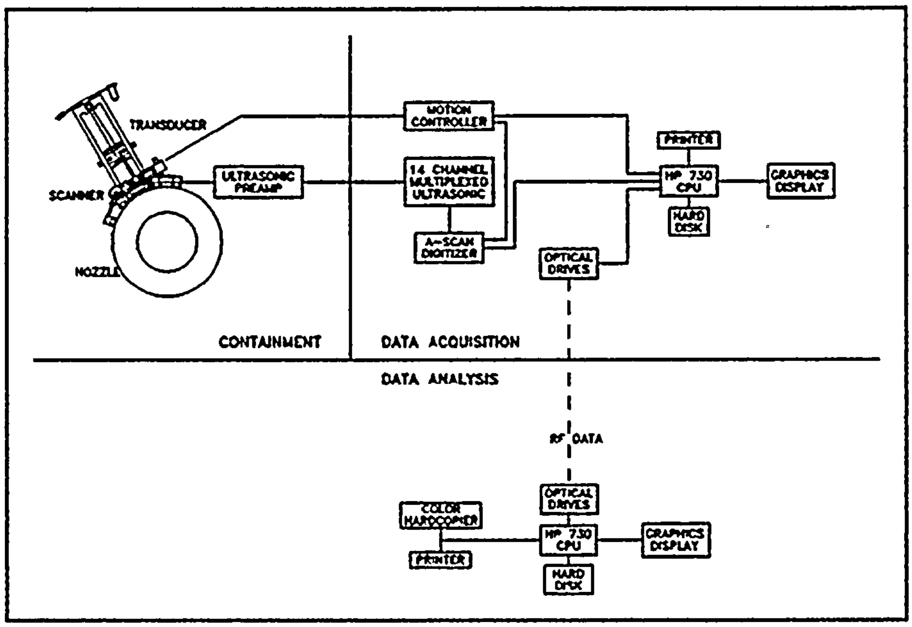

Figure 3
GERIS 2000 Nozzle Inspection System

Nozzle-Mounted Scanner

For scanning Zone 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.

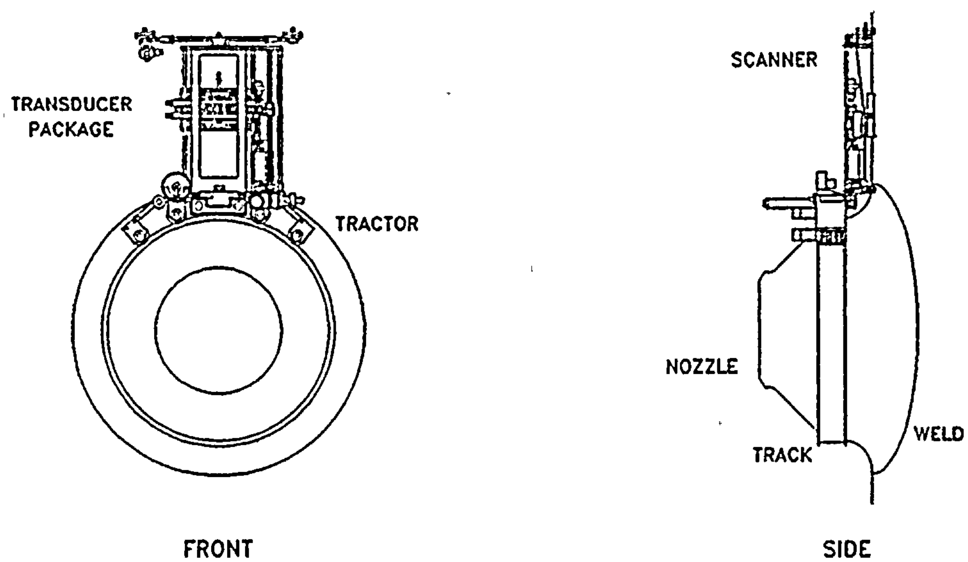

Figure 4
Nozzle-Mounted Scanner

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 Zones 2B, 3, 4 and 5.

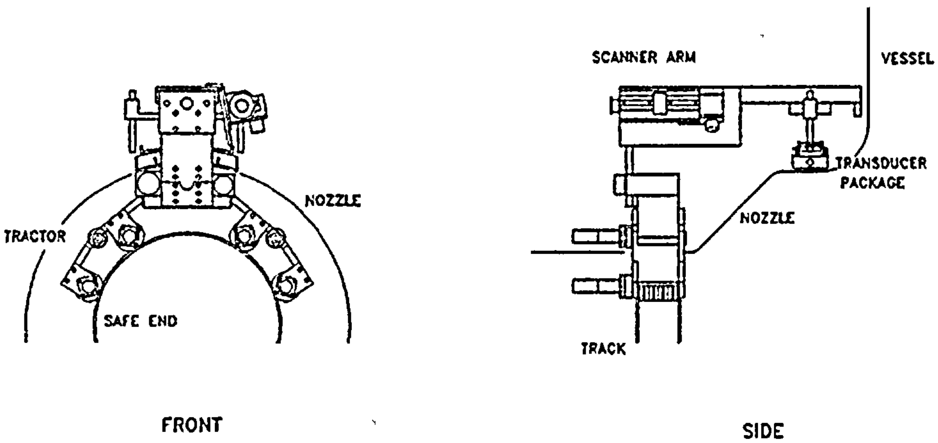

Figure 5
Safe-End Mounted Scanner

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 (Nozzle Scanner).

The nozzle inner-radius is examined from either the vessel plate or the nozzle OD blend radius surfaces.

Methods for examining from the vessel plate use refracted shear waves that pass through the nozzle-to-vessel weld. The sound beam and rotation angles are calculated assuming that the incident point of sound beam is located on the vessel surface and the axial-reflector location is typically at the center of the nozzle inner-radius. The sound beam is designed to intersect the inner-radius at a favorable angle. Sound beam and rotation angles are dependant 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 calculated by determining the optimal incident point of the sound beam on the nozzle OD blend radius with the axial reflector located at the center of the nozzle inner-radius. The sound beam and rotation angles are dependant 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.

The sound beam and rotation angles are calculated assuming that the incident point of the sound beam is located on the nozzle OD blend radius adjacent to the vessel surface. The axial reflector location is at the intersection point of Zones 2A and 2B. 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 Zone 1 region well into the Zone 2B area.

Zone 2B Examination (Safe-End Scanner).

The Zone 2B area of the nozzle bore is examined with refracted shear-waves from the nozzle OD cylindrical surface using the safe-end scanner (see Figure 5). Up to three separate (quarter, mid and three quarter point) refracted shear waves can be utilized to examine their respective areas on the nozzle bore. The terms quarter, mid and three-quarter point are designations for the three examination areas of the nozzle bore in Zone 2 (i.e., quarter-point being 1/4 of the Zone 2 length from Zone 1).

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 cylinderical surface using the safe end scanner (see Figure 5). 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 and taper-to-blend radius surfaces using the safe-end scanner (see Figure 5). Nozzles with small blend radius dimensions are normally examined with manual techniques.

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. This scan is performed with the safe end scanner (see Figure 5).

D. ULTRASONIC SUBSYSTEM

The UT 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 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-, volummetric side-view-, volummetric end-view- and 3D-scans are provided on a high resolution (1280 by 1024 pixels) color display. Several channels with all of the above mention 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 or to gray scale.

Real-time interaction between all displayed views (of a given scan) is automatic 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 6). 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.

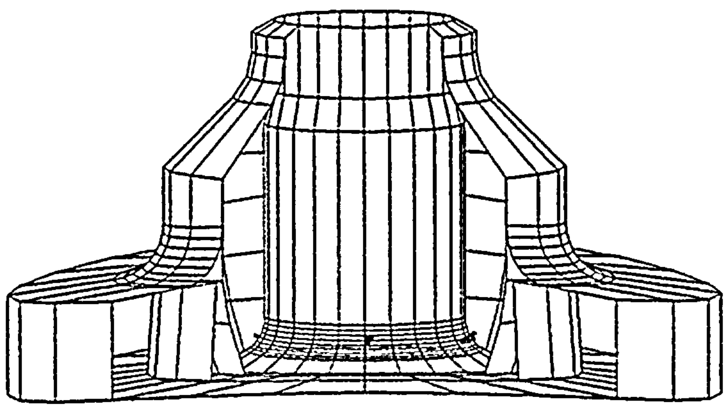

Figure 6
Nozzle Inner-Radius Data

The real-time A-scan is readily accessible and can be viewed for data analysis. Figure 7 is an A-scan display of a 0.170" deep nozzle inner-radius EDM notch in GE's clad-removed feedwater nozzle mockup. 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 supplant the NUREG 0619 PT exams.

Figure 7 A-Scan Display

F. FLAW SIZING

The sizing method used is totally dependant on the so-called 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.

The crack-tip signal is generally small in amplitude in comparison to the peak amplitude from the corner reflection. Depending on the interaction of the sound beam with the flaw and type of flaw, the crack-tip signal can be reduced by as much as 20 decibels (dB) or more in amplitude from that of the corner reflection.

III. ULTRASONIC TECHNIQUE QUALIFICATION PLAN

A. OVERVIEW

The ultrasonic qualification plan was 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 mock-ups, with flaws placed in the various inspection zones, were considered sufficient in the absence of protocol. Automatic 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 0.375" 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 scrutiny and review.

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 unclad 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 had a maximum flaw depth of 0.375", a more conservative condition than required. However, manual sizing techniques, which may be used to supplement the automated sizing data, were verified on notches with a maximum 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 mock-up 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 cancelled BWR.

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, and was 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.

The EDM notches were distributed throughout the examination volume. Notches were located in each inspection zone to demonstrate the individual testing technique for both detection and sizing. The notches are radially oriented as specified in Appendix VIII, which is also in accordance with fracture mechanics predictions and field experience with actual nozzle fatigue cracks.

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 inner radius. The unclad feedwater nozzle mockup used for implanting these fatigue cracks is from another cancelled BWR. The fatigue cracks were generated in material specimens the same as the nozzle forging.

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, nozzle taper and safe end. All the techniques that are presently used by GE were included in this qualification testing. Individual nozzle geometries will determine which of the above techniques will be applied.

A comparison of the EDM notch data and fatigue crack detection data showed that the amplitude responses of fatigue cracks and EDM notches of comparable depths were similar.

In summary, the fatigue cracks were equally detectable as the EDM notches. This coupled with the extensive qualification with the EDM notches provides confirmation of the effective of the UT system and techniques to detect fatigue cracking in the field.

SIZING

Sizing capabilities were qualified with the GERIS 2000 using the methodology of Appendix VIII. Manual techniques may be used to supplement the automated data, if necessary, during a field examination. For this qualification program, the EDM notches and the fatigue crack implants were sized with automated data from both directions. The sizing of flaws from both directions increases the data base for number of samples by a factor of two and better assesses sizing capabilities. The sizing acceptance criteria outlined in Appendix VIII was 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. In addition, the sizing results were acceptable to Appendix VIII criteria.

GE techniques developed over the past few years provide the means of performing routine quanitative inspections. These techniques have been developed to the point where they are now considered 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.

4) GE-NE-508-038-0394 Rev 1, "GERIS 2000 Ultrasonic Inspection of Feedwater Nozzles," GE Proprietary, GE Nuclear Energy, April 94.