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An Evaluation of Manual Ultrasonic Inspection of Cast Stainless Steel Piping

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Operated by
Battelle Memorial Institute

Prepared for
U.S. Nuclear Regulatory Commission

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AN EVALUATION OF MANUAL ULTRASONIC INSPECTION OF CENTRIFUGALLY CAST STAINLESS STEEL PIPING

T. T. Taylor

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ABSTRACT

This work was performed as a portion of a NRC research program entitled "Integration of Nondestructive Examination and Fracture Mechanics" (FIN. B2289). The NRC technical monitor is Dr. Joe Muscara.

Two studies have attempted to determine the degree of inspectability of centrifugally cast stainless steel (CCSS) pipe. In one study, Westinghouse examined the reliability of ultrasonic test methods in the detection of mechanical fatigue cracks. The second study was an NRC-sponsored Pipe Inspection Round Robin (PIRR) test conducted at Pacific Northwest Laboratory (PNL). The Westinghouse study reported that 80% detection was achieved for mechanical fatigue cracks having 20% through-wall depth. The PNL study reported that less than 30% detection was achieved for thermal fatigue cracks ranging from 5% to 50% through-wall.

A cooperative program between PNL and Westinghouse was conducted to resolve the differences between the two studies. The program was designed as a limited round robin. Detection experiments were performed on samples from both the PNL and Westinghouse studies.

The data reported here indicate that flaw type (thermal fatigue versus mechanical fatigue) was a significant factor in detection. Mechanical fatigue cracks were more easily detected than thermal fatigue cracks. The data conclusively show that manual ultrasonic inspection cannot size flaws in cast stainless steel material. The study recommends that ultrasonic inspection of cast stainless steel pipe be continued because cracks caused by some failure mechanisms (i.e., mechanical fatigue cracks) have proven to be detectable.

SUMMARY

The cost and relative corrosion resistance of Type 304 centrifugally cast stainless steel have resulted in extensive use of this material in the primary piping systems of pressurized water reactors. However, the manufacturing process of cast stainless steel results in a grain structure that affects propagation of ultrasound by causing severe attenuation, changes in velocity, and scattering of ultrasonic energy. These adverse acoustic properties cause ultrasonic examinations of cast stainless steel primary piping to be very difficult.

Two studies have attempted to determine the degree of inspectability of Centrifugally Cast Stainless Steel (CCSS) pipe. In one study, Westinghouse examined the reliability of ultrasonic test methods in the detection of mechanical fatigue cracks. The second study was an NRC-sponsored Pipe Inspection Round Robin (PIRR) conducted at Pacific Northwest Laboratory (PNL).

Test specimens used in the Westinghouse study were fabricated by welding pipe rings together with welding procedures typical of those used in the field. The welded pipe sections were cut longitudinally to produce specimens having 3-1/2 in. of the weld across the width of each specimen. Each specimen was then milled flat on the inner and outer surfaces of the weld to produce a specimen block. The specimen blocks would not produce any geometric indications. Final test specimens were placed under three-point loading and cycled until the desired crack depth was visible on both sides of the specimen. The study reported 80% detection without false calls for 20% through-wall cracks.

Test samples used in the PNL study were fabricated by welding two rings of cast stainless steel together. The welded rings were cut into 12-in.-long sections having 8 in. of the weld across the width of each specimen. The pipe samples contained blended weld crowns and counterbores which would not produce any geometric indications. Thermal fatigue cracks with intended depths ranging from 5% to 50% of wall thickness were induced in the pipe samples. The PNL study reported that less than 30% detection was achieved for thermal fatigue cracks with intended depths ranging from 5% to 50% through-wall.

A cooperative program between PNL and Westinghouse was conducted to resolve the differences between the two studies. The program was designed as a limited round robin. Detection experiments were performed on samples from both PNL and Westinghouse studies.

The data reported here indicate that flaw type (thermal fatigue versus mechanical fatigue) was a significant factor in detection. Mechanical fatigue cracks were more easily detected than thermal fatigue cracks. The data conclusively show that manual ultrasonic inspection cannot size flaws in cast stainless steel material. The study recommends that ultrasonic inspection of cast stainless steel pipe be continued because cracks caused by some failure mechanisms (i.e., mechanical fatigue cracks) have proven to be detectable.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

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AN EVALUATION OF MANUAL ULTRASONIC INSPECTION OF CENTRIFUGALLY CAST STAINLESS STEEL PIPING

1.0 INTRODUCTION

The cost and relative corrosion resistance of Type 304 cast stainless steel have resulted in extensive use of this material in the primary piping systems of pressurized water reactors (PWRs).

Inservice inspection requirements dictate that piping welds in the primary pressure boundary of light water reactors (LWRs) be subject to a volumetric examination based on the requirements of Section XI of the ASME Boiler and Pressure Vessel Code (ASME 1983). The volumetric examination may be either radiographic or ultrasonic. For inservice examinations, background radiation generally negates the use of radiography. Hence, cast austenitic welds in primary piping loops of LWRs are subject to inservice ultrasonic inspection.

The purpose of this report is to document the results of a joint Westinghouse and PNL effort to determine the limitations of inspectability of cast stainless steel using manual ultrasonic inspection techniques.

1.1 AN OVERVIEW OF THE INSPECTION PROBLEM

Processes for manufacturing centrifugally cast stainless steel (CCSS) pipe in the U.S. before 1976 resulted in a long, columnar grain structure with grain growth oriented along the direction of heat dissipation. Grains formed from this process attained several centimeters in length. After 1976, the process control was improved and a more equiaxed grain structure, similar to that found in an isostatic casting, was achieved. The two different grain structures have significantly different UT properties.

The large grain structure (either equiaxed or columnar) of cast stainless steel affects propagation of ultrasound by causing severe attenuation, changes in velocity, and scattering of ultrasonic energy.(1) Nonuniformities in the velocity of ultrasound cause refraction and reflection of the sound beam.(2) Refraction (i.e., bending) of the sound beam can cause the location of defects to be incorrectly reported, specific volumes of material not to be examined, or both. Coherent reflection and scattering of the sound beam at grain boundaries causes ultrasonic indications which are difficult to distinguish from flaw signals. When the above effects occur in the heavy-wall (approximately 3-in.-thick) piping found in the primary circuits of PWRs, ultrasonic examinations can be confusing, unpredictable, and unreliable.

1.2 CURRENT PROGRAM AND REPORT ORGANIZATION

Westinghouse and PNL conducted separate studies to determine the reliability of ultrasonic test methods for inspecting centrifugally cast stainless steel pipe.(3,4) Because the results of these two studies were contradictory, Westinghouse and PNL conducted a cooperative program to resolve the differences between the studies.

Section 2.0 of this report summarizes the two previous reliability studies. Section 3.0 describes the joint Westinghouse/PNL program and the program's experimental results. Section 4.0 discusses the experimental data from all three studies, and Section 5.0 summarizes conclusions and recommendations from all three studies.

2.0 PREVIOUS RELIABILITY STUDIES

One of the two recent studies on the inspectability of CCSS pipe was a Westinghouse study that involved the detection of mechanical fatigue cracks. The second study was an NRC-sponsored Pipe Inspection Round Robin (PIRR) conducted at Pacific Northwest Laboratory. Since this report addresses both studies, a summary of each follows.

2.1 SUMMARY OF WESTINGHOUSE RELIABILITY STUDY

In 1976 Westinghouse initiated a long-term program to determine the inspectability of CF8A, Type 304 cast stainless steel. The results were reported in "Reliability of Ultrasonic Test Methods for Detecting Natural Fatigue Cracks in Centrifugally Cast Stainless Steel Pipe."(3) The specific objective of the program was to determine the minimum through-wall dimension of mechanical fatigue cracks that could reliably be detected in centrifugally cast piping weldments by current practical ultrasonic testing. The program also evaluated inspection variables, including operator experience, crack location (whether inside or outside surface), and metallurgical structure of the weld (i.e. resulting from vertical, overhead, and downhand weld positions). All test specimens were made from a single section of pipe; hence, heat-to-heat variations in microstructure and grain structure variations (equiaxed versus columnar) were not addressed.

Test specimens were fabricated by welding pipe rings together with welding procedures typical of those used in the field. The welded pipe sections were cut longitudinally to produce specimens having 3-1/2 in. of the weld across each specimen. Each specimen was then milled flat on the inner and outer surfaces of the weld to eliminate geometric reflectors. Final test specimens were placed under three-point loading and cycled until the desired crack depth was visible on both sides of the specimen. Control samples containing no flaws were included in the test matrix to determine the inspector's ability to differentiate between metallurgical reflectors and fatigue flaws. All examinations were performed from both sides of the weld. Table 1 summarizes the results of the Westinghouse study for cracks that would have been located on the inside surface of the specimen.

The Westinghouse study reported that 80% detection was achieved without false calls for 20% through-wall cracks, and the reliability increased for cracks deeper than 20%. The study also showed that prior operator experience had little effect on performance, but that the operators became more proficient as they gained experience in examining these CCSS test samples.

The test specimens were "ideal" because there were no geometrical reflectors to hinder UT inspection. The mechanical fatigue cracks produced in the samples were very open and extended completely across the sample. Hence, the experimental estimates of detection reliability cannot be directly applied to the field inspections currently performed by any inservice inspection (ISI) organization. Field conditions such as non-optimum geometry at the inner diameter (ID) and outer diameter (OD), poor physical access, cracks under compressive stresses, and time limitations will adversely impact the inspection and lower the reliability figures. How much lower the results would be for field conditions is not known. Certainly the results reported by Westinghouse represent an upper bound of reliability for manual ultrasonic inspection of cast stainless steel.

2.2 Summary of PNL Reliability Study

In 1978 the Office of Nuclear Regulatory Research funded a program entitled "The Integration of Nondestructive Examination and Fracture Mechanics" at the Pacific Northwest Laboratory (PNL). One of the major program objectives was to determine the effectiveness and reliability of ISI. Part of the work required to meet this objective included conducting a pipe round robin in 1981 and 1982. A complete report of this work is in preparation and should be available during the summer of 1984.

Table 1

Summary of Westinghouse Test Results by Individual Test Operators

(Extracted from Pade and Enrietto, 1981, Ref. 3)

Specimen[a]	Oper	Weld Number - Crack Depth (% Through-Wall)[b]															Totals[b,c]		
																	P1+P2	+F	F*
OID	--	2-15	3-20	4-25	5-20	6-15	7-20	8-15	9-10	10-15	11-10	12-15	13-10	14-15	15-20	1-25	--	--	--
OID	1	F*	F*	P1	P1	P2	P1	P1	P2	P1	+F	P1	P2	F*	+F	P1	10	2	3
OID	2	+F*	P2	P1	P1	F*	P1	P1	P2	P1	+F	P1	+F	F*	P2	P1	10	3	3
OID	3	F*	P2	P1	P1	F*	P1	P1	+F	P1	+F	P1	P2	F*	P2	P1	10	2	3
DID	--	2-15	3-20	4-25	5-20	6-15	7-20	8-15	9-10	10-15	11-10	12-15	13-10	14-15	15-20	1-25	--	--	--
DID	1	P2	P1	P1	P1	P2	P2	P2	P1	F*	F*	F*	P1	P1	F*	F*	10	0	5
DID	2	+F	P1	P1	P1	+F	+F	+F	P1	P2	P2	P2	P1	P1	P2	P2	11	4	0
DID	3	P2	P1	P1	P1	F*	P2	P2	P1	P2	P2	P2	P1	P1	P2	F*	13	0	2
VID	--	2-15	3-20	4-25	5-20	6-15	7-20	8-15	9-20	10-15	11-10	12-15	13-10	14-5	15-10	1-15	--	--	--
VID	1	F*	F*	P1	P1	P2	P1	+F	P1	P1	P2	P1	P1	F*	P2	P2	11	1	3
VID	2	+F	+F	P1	P1	+F	P1	+F	P1	P1	+F	P1	P1	P2	P2	P2	10	5	0
VID	3	F*	+F	P1	P1	+F	P1	P2	P1	P1	F*	P1	P1	F*	+F	F*	8	3	4

a. OID = overhead weld position, ID crack; DID = downhand weld position, ID crack; VID = vertical weld position, ID crack

b. P1 = all operators passed test; P2 = at least one other operator failed test

c. +F = crack sample improperly characterized; F* = control sample improperly characterized

The objective of the round robin was to assess the reliability of current inservice pipe inspection, in terms of probabilities of defect detection and false call rates. The centrifugally cast stainless steel piping samples used in the round robin were fabricated by welding two rings of cast stainless together. The welded rings were cut into 12-in.-long sections having 8 in. of the weld across the width of each specimen. The pipe samples contained blended weld crowns and counterbores. The surface conditions of the samples would not produce geometric reflectors.

Thermal fatigue cracks were grown in the pipe samples. The intended depths ranged from 5% to 50% of wall thickness.

Six teams from commercial inservice inspection vendors participated in the round robin. Test protocol required each team to inspect the pipe samples using two ultrasonic testing (UT) procedures. First, inspection teams used their own field procedures; then a procedure written by PNL was used. A time limit of 30 minutes for data acquisition was imposed on teams, simulating field ALARA radiation dose constraints (ALARA - As Low As Reasonably Achievable). Finally, the teams' Level III inspector was not allowed to discover any UT indications in the specimens; he could only evaluate those indications specified for his attention by the Level II, since this is how UT indications are commonly handled in field ISI.

Results of the PNL round robin test for CCSS material are presented in Figure 1. The figure shows that no team achieved reliable detection. Of the six teams participating in the round robin, three teams detected less than 30% of the defects, the fourth achieved a higher score through gross overcall, and two declared a "no test," stating they had no confidence in their ability to inspect CCSS pipe.

The second part of the round robin test required each team to use a preselected instrument and search unit, and a UT procedure developed by PNL for optimized inspection of cast stainless steel. The ISI teams were allowed to practice with this equipment and procedure on cracked and uncracked CCSS specimens. The appearance and behavior of the crack signals were demonstrated to the teams. Then the teams completed another test matrix to measure their detection reliability with the "improved procedure." These results showed little or no improvement in detection reliability. A summary of the results is shown in Table 2.

The thermal fatigue cracks used in the test were very rough and ultrasonically tight. Reflected signals from the defects were generally no greater in amplitude than many of the metal-

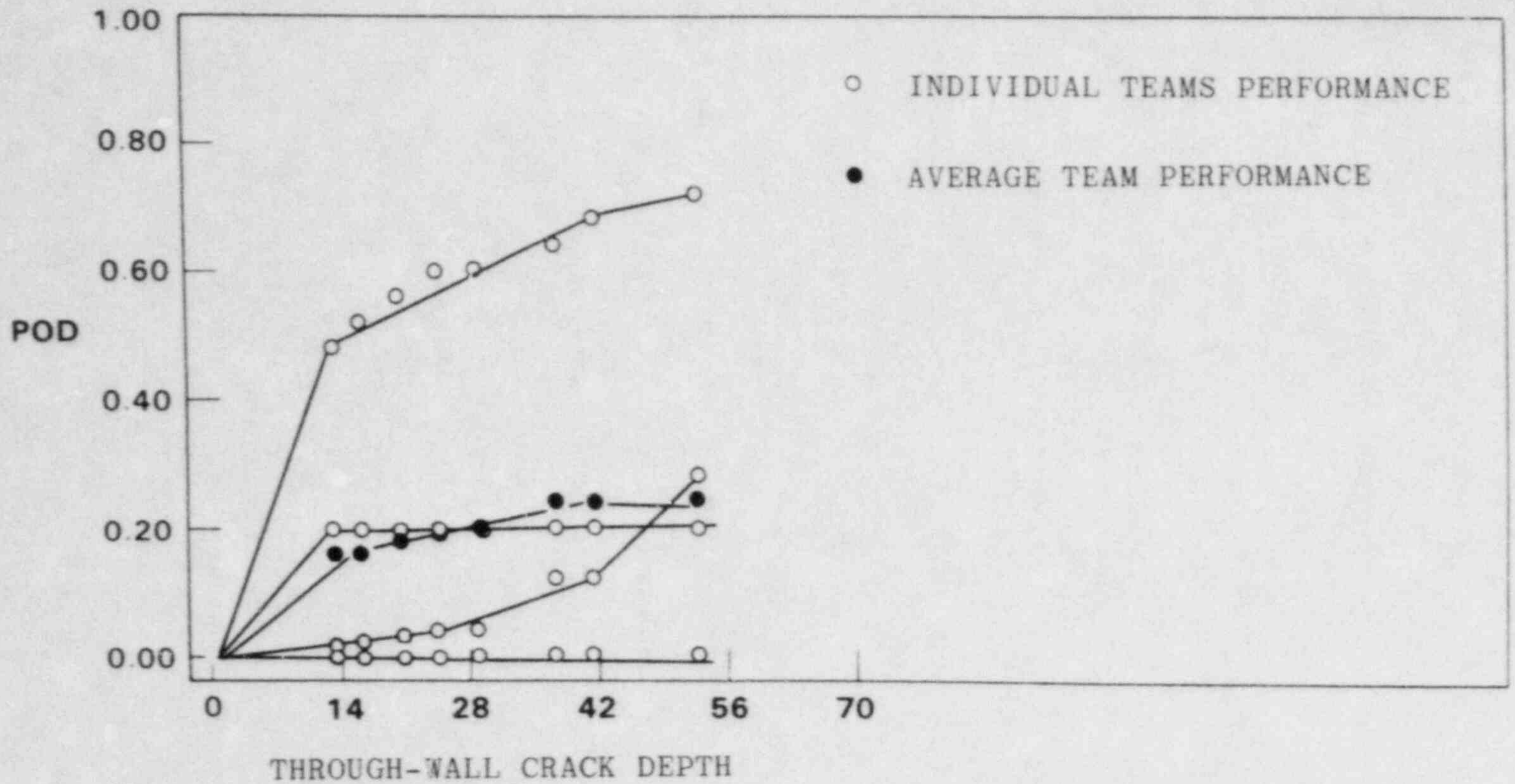

FIGURE 1. Plot of Probability of Detection (POD) Versus Crack Depth for the PNL Piping Inspection Round Robin

Table 2

Summary of the Results of the PNL Reliability Study

	Team		Crack Size (% Through-Wall) 0	12	16	20	24	28	36	40	52
Code Inspections	1	Detections/Inspections	0/8	0/1	0/1	0/1	0/8	0/8	0/4	0/4	0/5
	3		4/8	1/1	0/1	0/1	4/8	6/8	3/4	3/4	3/5
	5		2/9	0/1	0/1	0/1	2/8	2/9	1/3	1/4	0/4
	6		2/8	0/1	0/1	0/1	0/8	0/8	2/4	0/5	1/5
	All		8/35	1/4	0/4	0/4	6/33	8/34	6/16	4/18	4/27
Improved Inspections	All		6/20	-/-	0/5	1/5	1/25	0/5	-/-	4/5	2/15

lurgical reflectors present in the samples. The data from PNL's round robin are not a promising indication of reliable CCSS inspection.

3.0 JOINT WESTINGHOUSE/PNL EVALUATION

The contradictory results of the two reliability studies created a technical dilemma. Assurance of structural integrity requires that primary piping system joints in light water reactors be examined volumetrically (i.e., ultrasonically). If the reliability of ultrasonic inspection of cast stainless steel is as poor as indicated by the PNL study, adequate structural integrity of cast stainless steel primary piping cannot be assured by manual UT and alternative inspection techniques must be developed. If, however, the examination of cast stainless steel is as reliable as the Westinghouse study indicated, then structural integrity of primary piping systems can be assured.

Given the problem outlined above, PNL and Westinghouse collaborated on a program to resolve the apparent differences between the two studies and, if necessary, to suggest alternate inspection techniques.

3.1 Program Scope and Test Protocol

The cooperative program was designed as a limited round robin type of test. Only cast austenitic pipe specimens were examined. A field inspection team from Westinghouse examined both sets of test specimens. The field team had no prior experience with either set of test samples. The same test protocol as that used during the PNL PIRR (described below) was used during the cooperative study. It was felt that this procedure would allow analysis of both sets of test samples with a common team.

The round robin inspections were controlled by two persons: an observer, who continuously monitored the inspections, and a technician, who mounted the specimens in their holding jigs. The technician had a randomized list of all the inspections the team was to perform and the order of performance. The list was indexed by inspection number. Inspection numbers were used to uniquely identify each inspection in the experiment. The inspection number was also used in storing the inspection data in a computer data-base and in the raw data files.

The technician made certain that the inspection condition variables were set properly for each inspection. The critical variables were specimen type (i.e., Westinghouse or PNL) and access to flaw, either near side or far side. The observer completed the data forms, assembled the forms in an inspection folder, and filed them in the raw data file. In order to assure that all of the above was accomplished, the following test protocol was used:

1. The inspection to be performed was located on the randomized inspection list. This inspection was marked as "in processed" on the list.

2. The indicated weld specimen was removed from the specimen rack and mounted in a specimen jig with the proper weld side showing.

3. An inspection folder was labeled with the proper inspection number, and the header information on an inspection report form was completed (inspection number, team, environment, inspection procedure). This information was then attached to the specimen jig and transported to the inspection area.

4. When the team was ready for the next inspection, the prepared specimen was mounted on the inspection table.

5. The Level I and II team members were given 30 minutes to inspect the specimen and record all data on their company raw data sheets. As the Level I and II members proceeded to the next specimen, the specimen just inspected was presented to the Level III team member for evaluation. The Level III inspector evaluated the indications recorded by the Level I and II members and determined which, if any, of the indications were crack indications. The Level III member was not permitted to discover new indications; the intent was to simulate ISI, where a Level III inspector gets directly involved when Level I or II personnel call his attention to suspect areas of pipe. The Level III inspector also determined crack depth for any indications he determined to be cracks. When the evaluation was completed, the Level III filled out the "indications" section of the inspection report form, and the team members applied their signatures.

6. The observer collected all forms the teams had filled out during the course of the inspection, which included the calibration sheets and private raw data forms. These forms were put in the inspection folder and reattached to the specimen jig.

7. The specimen was wheeled back to the specimen racks, dismounted, and the specimen code and weld side were checked and recorded on the inspection report form. The inspection report form was reviewed for missing information and cor-

rected, if necessary. Before being returned to the specimen racks, all markings were cleaned off the specimen.

8. After completion of the previous tasks, the inspection was marked "completed" on the randomized inspection list, and the inspection folder was placed in the raw data file.

The technician was responsible for steps 1, 2, 3, 7, and 8. The observer was responsible for steps 4, 5, and 6. Note that the observer was unaware of the specimen's identity, presence or absence of cracks, crack locations and sizes, and near/far side access condition, preventing him from inadvertently giving the inspection team any of this important information.

3.2 EXPERIMENTAL RESULTS

3.2.1 Inspection Results

The results of the Westinghouse inspection team efforts on both Westinghouse samples and PNL samples is presented in Table 3.

When inspecting the CCSS specimens fabricated by Westinghouse, the inspection team performed as follows:

- When considering both cracked and uncracked specimens, the team properly characterized 17 of 22 samples.

- When considering cracked and uncracked specimens separately, the team properly characterized 9 of 14 cracked samples. All uncracked samples were characterized properly.

- None of the samples produced recordable indications along its entire length.

These results are in agreement with WCAP-9894. Detection probability was very good for cracks with depth greater than 15% through-wall.

For inspections of CCSS specimens that were made by PNL, the results followed the trend of the other four teams that inspected these specimens during the Pipe Inspection Round Robin. Out of 29 inspections of cracked specimens, only two cracks were detected. Again, none of the crack samples produced a recordable signal along its entire length. The only unusual feature of the Westinghouse team's performance was the absence of false calls.

Table 3

Results of Joint PNL/Westinghouse Study

Westinghouse Specimens:

Through-Wall Crack Depth	Number of Inspections	Number of Correct Calls	Number of Incorrect Calls
0%	8	8	0
14%	4	2	2[a]
15%	2	1	1[a]
19%	2	2	0
25%	2	2	0
29%	4	2	2[a]
	22	17	5

[a]Cracks were detected from the opposite side of the weld.

PNL Specimens:

Estimated Through-Wall Crack Depth[b]	Number of Inspections	Number of Correct Calls	Number of Incorrect Calls
0%	8	8	0
12%	1	0	1
16%	1	0	1
20%	1	0	1
24%	7	0	7
28%	7	0	7
36%	4	0	4
40%	3	1	2
52%	5	1	4
	37	10	27

[b]Destructive analysis of one sample showed crack depth to be approximately one-half of estimated depth.

It should be noted that the crack depths indicated for the PNL specimens were based on nondestructive measurements. Limited destructive measurements performed to date have indicated that the cracks were probably not this deep; in fact, it is estimated that the depth range of the PNL cracks was about the same as that of the Westinghouse specimens, viz., 0% to 30% through-wall.

3.2.2 Acoustic Velocity Characterization of Samples*

The acoustic velocity of both PNL and Westinghouse test samples was determined. The velocity measurements were made at normal incidence. Table 4 shows the results of the velocity measurements. Sample sets 1 and 2 are from specimens used during the PNL round robin and sample set 3 are specimens used in WCAP-9894.

Table 4

Velocity Measurements (Normal Incidence)

Sample	Microstructure	V_L Max (m/sec)	V_L Min (m/sec)
1 (PNL)	Equiaxed	5932	5875
2 (PNL)	Columnar	5496	5430
3 (Westinghouse)	Columnar*	5800	5420

*NOTE: Sample set 3 had very significant point-to-point variations (approximately 7%) within a single specimen.

After analyzing the velocity measurements, one can conclude the following:

- When considering all test samples, the acoustic velocity of CCSS material shows wide variation. This conclusion is not surprising and has been well documented.(5)

- The equiaxed and columnar microstructures of the PNL sample set have different, but well behaved velocities. The velocity of the equiaxed microstructure

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*The acoustic velocity characterization of the test samples was done by David S. Kupperman of Argonne National Laboratory.

has a maximum variation of 0.9%. The columnar microstructure has a maximum variation of 1.2%.

- The Westinghouse samples, by contrast, have wide variability from point-to-point within each sample and from sample-to-sample. The maximum variation of the Westinghouse samples is 7%.

4.0 DISCUSSION OF EXPERIMENTAL DATA

This discussion of these experimental results includes data from WCAP-9894, the PNL Piping Inspection Round Robin, and the joint study. The discussion focuses on topics that can be extracted from all three studies.

4.1 METALLURGY OF BASE MATERIAL

When the data were analyzed with respect to grain structure of the base metal, no trends appeared. Crack detection was either spread evenly between grain structure types (as was the case in the joint study) or false call rates were so high that trends were not statistically measurable after correction for false calls (as was the case for all PNL round robin data). The variability of velocity did not appear to affect crack detection. It does not appear from the experimental data that any particular grain structure (equiaxed or columnar) had better properties for ultrasonic inspection.

4.2 WELD ACCESS

Similarly, analysis of data from the joint study, PNL round robin, and WCAP-9894 does not show any clear trend for superior detection as a result of near-side or far-side access. However, access to both sides of a weld is a factor for improving crack detection.

4.3 DEFECT TYPE

The data analysis indicated that the most significant factor for crack detection is flaw type. The PNL samples contained ultrasonically tight, rough cracks. The tightness of the cracks was graphically illustrated when optimized radiographic examination of the samples had difficulty detecting all but the deepest cracks. The Westinghouse samples contain by comparison open and planar cracks. Both sets of test samples contained no geometric reflectors at the weld root or crown. The only signals interfering with crack detection were caused by metallurgical reflectors. Ultrasonic signals from cracks in the PNL samples were generally of very low amplitude, often no greater than signals reflected coherently from grain boundaries. By contrast, signals from the Westinghouse fatigue cracks were higher in amplitude; in fact, the response from all cracks was greater than or equal to the 3/16-in. side-drilled hole calibration reflector.

4.4 SIZING

WCAP-9894 did not address the subject of sizing at all; the PNL PIRR depth sizing data was too sparse for statistical analysis. However, those teams that did attempt to size did not do well. The experimental data from all three studies showed that no crack in either set of test samples produced detectable signals along its entire length. Therefore, it is concluded that current techniques applied in the field cannot accurately characterize either the length or depth of cracks in CCSS piping.

4.5 INSPECTION TECHNIQUE

During the PNL PIRR, all teams used dual-element longitudinal search units. Some of the search units used a zone isolation principle; some did not. The Westinghouse team used a search unit designed with a water column. None of the inspection techniques or search units showed superior performance.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The experimental data from the three studies suggest that detection of cracks in CCSS primary piping is highly dependent upon the cracking mechanism. Mechanical fatigue cracks have a reasonably high probability of detection; tight thermal fatigue cracks are essentially undetectable with current field ultrasonic inspection techniques. The most probable failure mechanism of cast stainless steel pipe is not known at this time. However, some failure mechanisms (i.e., mechanical fatigue) have proven to be detectable; therefore, the following recommendation -

- Continue the requirement of ultrasonic examination of cast stainless steel pipe.

Data from the Westinghouse study indicate that operator training can improve detection efficiency; therefore, this recommendation -

- Use actual flawed specimens to train operators involved in the inspection of CCSS piping and require some demonstration analagous to that described in IEB 8[illegible]-02.

Limited destructive analysis of the PNL PIRR flaws indicated that the true flaw depths may be less than the intended depths. Therefore, insufficient data exists to predict the detectability of thermal fatigue cracks deeper than 30% wall thickness. The following recommendations are made to provide a better definition of detectability for safety-significant, rough, tight flaws.

- Using PNL type samples, produce cracks with through-wall depths ranging between 50% and 75% of pipe thickness and determine whether or not crack detection improves significantly for deeper cracks.

- Establish the critical flaw size (maximum safe length and through-wall depth dimensions) for CCSS pipe.

The most troublesome evidence from all three studies is the conclusive data showing the inability of current field practices to properly characterize cracks in CCSS. The only area of defect sizing that has not been properly addressed is the potential of more sophisticated techniques such as SAFT-UT, UDRPS, and holography; therefore, a final recommendation -

- Evaluate the potential of more sophisticated techniques (such as SAFT-UT, UDRPS, and holography) for examining CCSS piping.

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This work was performed as a portion of a NRC research program entitled "Integration of Nondestructive Examination and Fracture Mechanics" (FIN. B2289). The NRC technical monitor is Dr. Joe Muscara. Two studies have attempted to provide an answer to the degree of inspectability of Centrifugally Cast Stainless Steel (CCSS) pipe. One study was an NRC-sponsored Pipe Inspection Round Robin (PIRR) test conducted at Pacific Northwest Laboratory (PNL). Another study was conducted by Westinghouse. The PNL study reported that less than 30% detection was achieved on thermal fatigue cracks ranging from 5% to 50% through-wall. The Westinghouse study reported that 80% detection was achieved for 20% through-wall mechanical fatigue cracks. A cooperative program between PNL and Westinghouse was conducted to resolve the differences between the two studies. The program was designed as a limited round robin. Detection experiments were performed on samples from both the PNL and Westinghouse studies. The data reported here indicates that flaw type (thermal fatigue versus mechanical fatigue) was a significant factor in detection. Mechanical fatigue cracks were more easily detected than thermal fatigue cracks. The data conclusively shows that manual ultrasonic inspection cannot size flaws in cast stainless steel material. The study recommends that ultrasonic inspection of cast stainless steel pipe be continued because some failure mechanisms (i.e., mechanical fatigue cracks) have proven to be detectable.

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