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Nondestructive Examination (NDE) Reliability for Inservice Inspection of Light Water Reactors

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Abstract

The Evaluation and Improvement of NDE Reliability for Inservice Inspection of Light Water Reactors (NDE Reliability) Program at the Pacific Northwest Laboratory was established by the Nuclear Regulatory Commission to determine the reliability of current inservice inspection (ISI) techniques and to develop recommendations that will ensure a suitably high inspection reliability. The objectives of this program include determining the reliability of ISI performed on the primary systems of commercial light-water reactors (LWRs); using probabilistic fracture mechanics analysis to determine the impact of NDE unreliability on system safety; and evaluating reliability improvements that can be achieved with improved and advanced technology. A final objective is to formulate recommended revisions to the Regulatory and ASME Code requirements, based on material properties, service conditions, and NDE uncertainties. The program scope is limited to ISI of the primary systems including the piping, vessel, and other components inspected in accordance with Section XI of the ASME Code. This is a progress report covering the programmatic work from October 1990 through March 1991.

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Executive Summary[1]

A multi-year program entitled the Evaluation and Improvement of NDE Reliability for Inservice Inspection of Light Water Reactors (NDE Reliability) was established at the Pacific Northwest Laboratory (PNL) to determine the reliability of current inservice inspection (ISI) techniques and to develop recommendations that would ensure a suitably high inspection reliability if fully implemented.

The objectives of this Nondestructive Examination (NDE) Reliability program for the Nuclear Regulatory Commission (NRC) include:

- Determine the reliability of ultrasonic ISI performed on the primary systems of commercial light-water reactors (LWRs).

- Use probabilistic fracture mechanics analysis to determine the impact of NDE unreliability on system safety and determine the level of inspection reliability required to ensure a suitably low failure probability.

- Evaluate the degree of reliability improvement that could be achieved using improved and advanced NDE techniques.

- Based on material properties, service conditions, and NDE uncertainties, formulate recommended revisions to Sections XI and V of the ASME Code and the Regulatory requirements needed to ensure suitably low failure probabilities.

The scope of the program is limited to the ISI of primary coolant systems, but the results and recommendations are also applicable to Class 2 piping systems.

The program consists of three basic tasks: a Piping task, a Pressure Vessel task, and a New Inspection Criteria task. The major program highlights during this reporting period were:

- ASME Code Activity

  Participation in ASME Section XI activities continued toward achieving Code acceptance of NRC-funded PNL research results to improve the reliability of nondestructive evaluation/inservice inspection (NDE/ISI). Minutes of ASME Section XI Subgroup on Nondestructive Examination (SGNDE) meetings held December 1990 in Anaheim, CA and February 1991 in San Diego, CA were prepared and distributed. PNL recommendations for revising Appendix VIII-4000 to limit the center frequency tolerance for narrow-band UT systems was approved by the SGNDE. In conjunction with an on-going SGNDE action item to consider adoption of the new ASNT PQ standard, PNL personnel reviewed this document and provided comments for the SGNDE minutes as well as for the ASNT Canvass Committee. An activity to develop performance demonstration requirements for eddy current data analysts is continuing.

- Pressure Vessel Inspection

  Re-Analysis of PISC-II Data. The objective of this task is to determine the capability of U.S. ultrasonic inservice inspection of reactor pressure vessels. This objective is to be accomplished by utilizing data from the PISC-II round robin trials. Awaiting comments from the NRC on a revised document that had been resubmitted to NRC. No work was performed during this reporting period. The final version of this report will be submitted to the NRC program manager when completed.

  Equipment Interaction Matrix. The objective of this work is to evaluate the effects of frequency domain equipment interactions and determine tolerance values for improving ultrasonic inspection reliability. Calculations were performed to determine the sensitivity of 45° and 60° SV pulse-echo inspection results to changes in equipment parameters when thick (6-12 in.) steel specimens are examined. These results were essentially the same as those found for thin steel plate. The existing ASME Code requirements for equipment center frequency were again found to be inadequate, as they were when thin sections were considered. Model performance was improved by modifying the computer software to run 10 times faster. A presentation was given to the cognizant ASME Section XI Code committees, and a paper was prepared for the 10th International Conference on NDE in the Nuclear Industry.

[1]RSR FIN Budget No. B2289; RSR Contact: J. Muscara

- New Inspection Criteria

  Work continued on assessments of the adequacy of existing ASME Code requirements for ISI and on developing technical bases for improved ISI requirements that will contribute to high nuclear power plant component structural integrity. Development of a comprehensive probabilistic approach for improved inspection requirements moved forward. A major focus of this effort has continued to be participation in an ASME Research Task Force on Risk-Based Inspection Guidelines.

  Calculations during this reporting period have applied probabilistic risk assessment (PRA) to establish inspection priorities for pressure boundary systems and components. Plant-specific risk-based studies have been for the Surry Unit 1 Nuclear Power Station. This effort is being performed with the cooperation of Virginia Electric Power Company, and involved two additional plant visits during this reporting period for system walkdowns and detailed interviews with plant staff. Estimates of failure probabilities have been an important input to the risk-based calculations for Surry-1. Data from an expert judgement elicitation performed in May of 1990 have been analyzed to estimate rupture probabilities for components in four critical systems (reactor pressure vessel, reactor coolant system, low pressure injection system and auxiliary feedwater system). A preliminary ranking of components in these four systems for ISI prioritization has been completed.

- Consult on Field Problems

  The objective of this work is to provide a rapid response to urgent and unexpected problems as they are identified by the Office of Nuclear Regulatory Research. No work was identified to be performed on this subtask during this reporting period.

- Piping Inspection Task

  This task is designed to address the NDT problems associated with piping used in light water reactors. The primary thrust of the work has been on wrought and cast stainless steel since these materials are harder to inspect than carbon steel. However, many of the subtasks' results also pertain to carbon steel. The current subtasks are: cast stainless steel inspection, surface roughness, field pipe characterization, and PISC-III activities.

  Cast Stainless Steel Inspection. The objective of this subtask is to evaluate the effectiveness and reliability of ultrasonic inspection of cast materials within the primary pressure boundary of LWRs. Activities for this reporting period included microstructural classification of CCSS material within the PISC NDW Assembly 25 block, use of the Rayleigh critical angle technique to characterize CCSS microstructure, draft input to a proposed cooperative work effort between NRC (PNL) and UKAEA, a paper on phase mapping of ultrasonic fields in CCSS, and preparation of a white paper proposing the use of adaptive ultrasonics to compensate for distortion caused by cast grain structures.

  Surface Roughness. The objective of this work was to establish specifications such that an effective and reliable ultrasonic inspection is not precluded by the condition of the surface from which the inspection is conducted. Activities for this reporting period included further refinement of the model by CNDE and development of better experimental procedures by PNL for obtaining quantitative data to compare with model predictions. Delays occurred in model refinement due to funding problems for CNDE.

  Field Pipe Characterization. The objective of this subtask is to provide pipe weld specimens that can be used for studies to evaluate the effectiveness and reliability of ultrasonic inservice inspection (UT/ISI) performed on BWR piping. Documentation of the five safe-ends removed from the Monticello nuclear power station are no longer needed for any programmatic work. Processes to dispose of these samples are under review to meet the new requirements for disposal required by state and federal agencies.

  PISC III. This activity involves participation in the PISC-III program to ensure that the work addresses NDE reliability problems for materials and ISI practices on U.S. LWRs. This includes support for the co-leader of Action 4 on Austenitic Steel Tests (AST); coordination of participation by U.S. teams on various Actions; and input to the studies on human reliability, specimens for use in the Parametric, Capability, and Reliability studies of the AST, following work being performed under Action 2 on Full-Scale Vessel Tests (FSV), Action 3 on Nozzles and Dissimilar Metal Welds, and also tracking the PISC-III work and relaying points of interest and concerns to the NRC that may arise from the analysis of the newly created and evolving data base.

Previous Reports in Series

Green, E. R., S. R. Doctor, R. L. Hockey, and A. A. Diaz. 1992. *The Interaction Matrix Study: Models and Equipment Sensitivity Studies for the Ultrasonic Inspection of Thin Wall Steel.* NUREG/CR-5817. Pacific Northwest Laboratory, Richland, Washington.

Doctor, S. R., M. S. Good, P. G. Heasler, R. L. Hockey, F. A. Simonen, J. C. Spanner, T. T. Taylor, and T. V. Vo. 1992. *Nondestructive Examination (NDE) Reliability for Inservice Inspection of Light Water Reactors.* NUREG/CR-4469, PNL-5711, Vol. 12. Pacific Northwest Laboratory, Richland, Washington.

Doctor, S. R., M. S. Good, E. R. Green, P. G. Heasler, F. A. Simonen, J. C. Spanner, T. T. Taylor, and T. V. Vo. 1991. *Nondestructive Examination (NDE) Reliability for Inservice Inspection of Light Water Reactors.* NUREG/CR-4469, PNL-5711, Vol. 11. Pacific Northwest Laboratory, Richland, Washington.

Heasler, P. G., T. T. Taylor, J. C. Spanner, S. R. Doctor, and J. D. Deffenbaugh. 1990. *Ultrasonic Inspection Reliability for Intergranular Stress Corrosion Cracks: A Round Robin Study of the Effects of Personnel, Procedures, Equipment and Crack Characteristics.* NUREG/CR-4908. Pacific Northwest Laboratory, Richland, Washington.

Spanner, J. C., S. R. Doctor, T. T. Taylor/PNL and J. Muscara/NRC. 1990. *Qualification Process for Ultrasonic Testing in Nuclear Inservice Inspection Applications.* NUREG/CR-4882, PNL-6179. Pacific Northwest Laboratory, Richland, Washington.

Doctor, S. R., J. D. Deffenbaugh, M. S. Good, E. R. Green, P. G. Heasler, F. A. Simonen, J. C. Spanner, T. T. Taylor, and T. V. Vo. 1990. *Nondestructive Examination (NDE) Reliability for Inservice Inspection of Light Water Reactors.* NUREG/CR-4469, PNL-5711, Vol. 10. Pacific Northwest Laboratory, Richland, Washington.

Doctor, S. R., J. D. Deffenbaugh, M. S. Good, E. R. Green, P. G. Heasler, F. A. Simonen, J. C. Spanner, and T. T. Taylor. 1989. *Nondestructive Examination (NDE) Reliability for Inservice Inspection of Light Water Reactors.* NUREG/CR-4469, PNL-5711, Vol. 9. Pacific Northwest Laboratory, Richland, Washington.

Doctor, S. R., J. D. Deffenbaugh, M. S. Good, E. R. Green, P. G. Heasler, F. A. Simonen, J. C. Spanner, and T. T. Taylor. 1989. *Nondestructive Examination (NDE) Reliability for Inservice Inspection of Light Water Reactors.* NUREG/CR-4469, PNL-5711, Vol. 8. Pacific Northwest Laboratory, Richland, Washington.

Doctor, S. R., J. D. Deffenbaugh, M. S. Good, E. R. Green, P. G. Heasler, F. A. Simonen, J. C. Spanner, and T. T. Taylor. 1988. *Nondestructive Examination (NDE) Reliability for Inservice Inspection of Light Water Reactors.* NUREG/CR-4469, PNL-5711, Vol. 7. Pacific Northwest Laboratory, Richland, Washington.

Doctor, S. R., J. D. Deffenbaugh, M. S. Good, E. R. Green, P. G. Heasler, G. A. Mart, F. A. Simonen, J. C. Spanner, T. T. Taylor, and L. G. Van Fleet. 1987. *Nondestructive Examination (NDE) Reliability for Inservice Inspection of Light Water Reactors.* NUREG/CR-4469, PNL-5711, Vol. 6. Pacific Northwest Laboratory, Richland, Washington.

Doctor, S. R., D. J. Bates, J. D. Deffenbaugh, M. S. Good, P. G. Heasler, G. A. Mart, F. A. Simonen, J. C. Spanner, T. T. Taylor, and L. G. Van Fleet. 1987. *Nondestructive Examination (NDE) Reliability for Inservice Inspection of Light Water Reactors.* NUREG/CR-4469, PNL-5711, Vol. 5. Pacific Northwest Laboratory, Richland, Washington.

Doctor, S. R., D. J. Bates, J. D. Deffenbaugh, M. S. Good, P. G. Heasler, G. A. Mart, F. A. Simonen, J. C. Spanner, A. S. Tabatabai, T. T. Taylor, and L. G. Van Fleet. 1987. *Nondestructive Examination (NDE) Reliability for Inservice Inspection of Light Water Reactors.* NUREG/CR-4469, PNL-5711, Vol. 4. Pacific Northwest Laboratory, Richland, Washington.

Collins, H. D. and R. P. Gribble. 1986. *Siamese Imaging Technique for Quasi-Vertical Type (QVT) Defects in Nuclear Reactor Piping.* NUREG/CR-4472, PNL-5717. Pacific Northwest Laboratory, Richland, Washington.

Doctor, S. R., D. J. Bates, R. L. Bickford, L. A. Charlot, J. D. Deffenbaugh, M. S. Good, P. G. Heasler, G. A. Mart, F. A. Simonen, J. C. Spanner, A. S. Tabatabai, T. T. Taylor, and L. G. Van Fleet. 1986. *Nondestructive Examination (NDE) Reliability for Inservice Inspection of Light Water Reactors.* NUREG/CR-

4469, PNL-5711, Vol. 3. Pacific Northwest Laboratory, Richland, Washington.

Doctor, S. R., D. J. Bates, L. A. Charlot, M. S. Good, H. R. Hartzog, P. G. Heasler, G. A. Mart, F. A. Simonen, J. C. Spanner, A. S. Tabatabai, and T. T. Taylor. 1986. *Evaluation and Improvement of NDE Reliability for Inservice Inspection of Light Water Reactors.* NUREG/CR-4469, PNL-5711, Vol. 2. Pacific Northwest Laboratory, Richland, Washington.

Doctor, S. R., D. J. Bates, L. A. Charlot, H. D. Collins, M. S. Good, H. R. Hartzog, P. G. Heasler, G. A. Mart, F. A. Simonen, J. C. Spanner, and T. T. Taylor. 1986. *Integration of Nondestructive Examination (NDE) Reliability and Fracture Mechanics, Semi-Annual Report, April 1984 - September 1984.* NUREG/CR-4469, PNL-5711, Vol. 1. Pacific Northwest Laboratory, Richland, Washington.

Good, M. S. and L. G. Van Fleet. 1986. *Status of Activities for Inspecting Weld Overlaid Pipe Joints.* NUREG/CR-4484, PNL-5729. Pacific Northwest Laboratory, Richland, Washington.

Heasler, P. G., D. J. Bates, T. T. Taylor, and S. R. Doctor. 1986. *Performance Demonstration Tests for Detection of Intergranular Stress Corrosion Cracking.* NUREG/CR-4464, PNL-5705, Pacific Northwest Laboratory, Richland, Washington.

Simonen, F. A. 1984. *The Impact of Nondestructive Examination Unreliability on Pressure Vessel Fracture Predictions.* NUREG/CR-3743, PNL-5062. Pacific Northwest Laboratory, Richland, Washington.

Simonen, F. A. and H. H. Woo. 1984. *Analyses of the Impact of Inservice Inspection Using Piping Reliability Model.* NUREG/CR-3753, PNL-5070. Pacific Northwest Laboratory, Richland, Washington.

Taylor, T. T. 1984. *An Evaluation of Manual Ultrasonic Inspection of Cast Stainless Steel Piping.* NUREG/CR-3753, PNL-5070. Pacific Northwest Laboratory, Richland, Washington.

Bush, S. H. 1983. *Reliability of Nondestructive Examination, Volumes I, II, and III.* NUREG/CR-3110-1, -2, and -3; PNL-4584. Pacific Northwest Laboratory, Richland, Washington.

Simonen, F. A. and C. W. Goodrich. 1983. *Parametric Calculations of Fatigue Crack Growth in Piping.* NUREG/CR-3059, PNL-4537. Pacific Northwest Laboratory, Richland, Washington.

Simonen, F. A., M. E. Mayfield, T. P. Forte, and D. Jones. 1983. *Crack Growth Evaluation for Small Cracks in Reactor-Coolant Piping.* NUREG/CR-3176, PNL-4642. Pacific Northwest Laboratory, Richland, Washington.

Taylor, T. T., S. L. Crawford, S. R. Doctor, and G. J. Posakony. 1983. *Detection of Small-Sized Near-Surface Under-Clad Cracks for Reactor Pressure Vessels.* NUREG/CR-2878, PNL-4373. Pacific Northwest Laboratory, Richland, Washington.

Busse, L. J., F. L. Becker, R. E. Bowey, S. R. Doctor, R. P. Gribble, and G. J. Posakony. 1982. *Characterization Methods for Ultrasonic Test Systems.* NUREG/CR-2264, PNL-4215. Pacific Northwest Laboratory, Richland, Washington.

Morris, C. J. and F. L. Becker. 1982. *State-of-Practice Review of Ultrasonic In-service Inspection of Class I System Piping in Commercial Nuclear Power Plants.* NUREG/CR-2468, PNL-4026. Pacific Northwest Laboratory, Richland, Washington.

Becker, F. L., S. R. Doctor, P. G. Heasler, C. J. Morris, S. G. Pitman, G. P. Selby, and F. A. Simonen. 1981. *Integration of NDE Reliability and Fracture Mechanics, Phase I Report.* NUREG/CR-1696-1, PNL-3469. Pacific Northwest Laboratory, Richland, Washington.

Taylor, T. T. and G. P. Selby. 1981. *Evaluation of ASME Section XI Reference Level Sensitivity for Initiation of Ultrasonic Inspection Examination.* NUREG/CR-1957, PNL-3692. Pacific Northwest Laboratory, Richland, Washington.

1.0 Introduction

The Evaluation and Improvement of NDE Reliability for Inservice Inspection of Light Water Reactors (NDE Reliability) Program at Pacific Northwest Laboratory (PNL) was established to determine the reliability of current inservice inspection (ISI) techniques and to develop recommendations that would ensure a suitably high inspection reliability if fully implemented. The objectives of this program for the Nuclear Regulatory Commission (NRC) are:

- Determine the reliability of ultrasonic ISI performed on commercial lightwater reactor (LWR) primary systems.
- Use probabilistic fracture mechanics analysis to determine the impact of NDE unreliability on system safety and determine the level of inspection reliability required to insure a suitably low failure probability.
- Evaluate the degree of reliability improvement that could be achieved using improved and advanced NDE techniques.
- Based on material properties, service conditions, and NDE uncertainties, formulate recommended revisions to Section XI of the Regulatory and ASME Code requirements needed to ensure suitably low failure probabilities.

The scope of this program is limited to ISI of primary coolant systems, but the results and recommendations are also applicable to Class 2 piping systems.

The program consists of three basic tasks: a Piping task, a Pressure Vessel task, and a New Inspection Criteria task. This report is divided into the following sections.

- ASME Code Related Activities
- Pressure Vessel Inspection
- New Inspection Criteria
- Consult on Field Problems
- Piping Task Activities

2.0 ASME Code Related Activities

2.1 Summary

Participation in ASME Section XI activities continued toward achieving Code acceptance of NRC-funded PNL research results to improve the reliability of nondestructive evaluation/inservice inspection (NDE/ISI). Minutes of ASME Section XI Subgroup on Nondestructive Examination (SGNDE) meetings held December 1990 in Anaheim, CA and February 1991 in San Diego, CA were prepared and distributed. PNL recommendations for revising Appendix VIII-4000 to limit the center frequency tolerance for narrow-band UT systems was approved by the SGNDE. In conjunction with an ongoing SGNDE action item to consider adoption of the new ASNT PQ standard, PNL personnel reviewed this document and provided comments for the SGNDE minutes as well as for the ASNT Canvass Committee. An activity to develop performance demonstration requirements for eddy current data analysts is continuing.

2.2 Introduction

One objective of this task is to develop and/or evaluate new criteria and requirements for achieving acceptable and reliable ultrasonic testing/inservice inspection (UT/ISI). The ultimate goal is for these criteria and requirements to be incorporated into Sections V and XI (SC-V and SC-XI) of the ASME Boiler and Pressure Vessel Code. If that goal cannot be met or if the requirements adopted by the ASME Code are inadequate, PNL may also be requested to prepare draft Regulatory Guide input as a back-up approach.

To implement this goal, PNL staff members are active participants in Section V and Section XI ASME Code committee activities. PNL staff members serve as Secretary of the SC-XI SGNDE, chair a Special SC-XI Task Group to develop acoustic emission requirements, and serve as members of the SC-XI Working Group on Surface Examination and Personnel Qualification and the SC-XI Working Group on Volumetric Examination and Procedure Qualification. In addition, PNL personnel serve as members of the SC-V Working Group on Ultrasonic Testing and the SC-V Working Group on Acoustic Emission. Additionally, administrative assistance is provided in support of related efforts to achieve Code acceptance of new personnel qualification (PQ) and performance demonstration (PD) requirements for eddy current equipment operators and data analysts, and a new SC-V activity to develop requirements and criteria for computerized UT imaging systems.

2.3 Status of Work Performed

Proactive participation of PNL personnel in ASME Code activities continued toward achieving Code acceptance of NRC-funded PNL research results to improve the reliability of NDE/ISI. During this reporting period, meetings of the ASME Section XI Subcommittee (including relevant Subgroup and Working Group meetings) were attended December 10-13, 1990 in Anaheim, CA and February 4-7, 1991 in San Diego, CA. Agendas and minutes of the SGNDE meetings held in conjunction with the Section XI Subcommittee meetings were prepared and distributed. In addition, meetings of the Section V Subcommittee on Nondestructive Examination [specifically the Subgroup on Ultrasonic Testing (SGUT), the Subgroup on Acoustic Emission (SGAE), and the Subgroup on General Requirements/Surface Examination (SGGR/SE)] were attended in Anaheim, CA on December 10-11, 1990.

Proposed new Section XI criteria and requirements for applying the acoustic emission method for Section XI applications were prepared in Code Case format. This proposed new Code Case on acoustic emission was approved by the SGNDE, SC-XI, and the ASME Main Committee (M.C.) during the previous reporting period. During this reporting period, the finalized version of this proposed Code Case was approved by the Board on Nuclear Codes and Standards (BNCS) for publication in Supplement No. 5 to the ASME Code Cases for Nuclear Components. This Code Case was designated N-471 and is entitled "Acoustic Emission for Successive Inspections Required by Section XI, Div. 1."

Proposed new Code requirements are being drafted to encourage broader utilization of the synthetic aperture focusing technique (SAFT) technology developed under NRC-sponsored research programs at PNL and the University of Michigan. These requirements were submitted to the ASME SC-V Subgroup on Ultrasonic Testing (SGUT) to fulfill the need for Code rules to cover the computerized UT imaging systems that are being utilized by the NDE/ISI industry for examining critical nuclear power plant components. During the December 1990 SGUT meeting, the initial outline for the proposed Section T-435 was expanded to include the following:

T-435	Computerized Imaging Systems
T-435.1	Description and Application
T-435.2	General Requirements
T-435.3	Specific Requirements
T-435.4	Calibration
T-435.5	Data Acquisition
T-435.6	Signal/Data Storage and Retention
T-435.7	Terms and Definitions
T-435.8	Procedures/Output/Display
T-435.9	Auditability
T-435.10	Signal Processing
T-435.11	Output/Image Display
T-435.12	Measurement
T-435.13	Supplemental Evaluation Systems (SAFT, Holography, etc.)

Proposed text for the new Section T-435.13 entitled "Supplemental Evaluation Systems (SAFT, Holography, etc.)" was prepared and distributed to the Task Group members. Although other Task Group members had accepted assignments to prepare the T-435 paragraphs outlined above, the response to these commitments was disappointing. However, we intend to continue to pursue this activity.

A joint meeting of the SC-V SGAE and the SC-XI Task Group on AE was held in Anaheim, CA in December 1990. During this meeting, the proposed scope of a new Section V Article on AE monitoring of inservice vessels was refined to accommodate Section XI needs and criteria.

During the December 1990 SGNDE meeting, it was reported that the Industry Ad Hoc Committee on Appendix VIII Implementation had held an information meeting in September 1990 in Atlanta, GA involving about 120 attendees representing a broad cross-section of industry. During the February 1991 SGNDE meeting in San Diego, CA it was reported that the Utility Ad Hoc Committee for Appendix VIII Implementation became a permanent Steering Committee in January 1991. At that time, paid utility participation included about 95 of 112 operating nuclear units. The four major committee projects for 1991 were: a) develop technical specifications for the Regional test centers, b) complete the implementation guidelines for Appendix VIII, c) develop a UT modeling capability to design examination techniques and provide a means to transfer a qualified UT examination technique to a similarly configured component, and d) procure/fabricate flawed specimens.

Revised visual acuity requirements for NDE personnel were developed and approved for publication in the 1991 Addenda to Section XI. A new requirement for generic practical examinations for Level III NDE personnel was also approved by the BNCS for publication in the 1991 Addenda. A Main Committee Task Group has been appointed to study a proposal for Code adoption of the 1988 Edition of SNT-TC-1A, as well as to evaluate the new ASNT Standard on Personnel Qualification.

2.4 Future Work

Minutes for the ASME Section XI SGNDE meeting held February 1991 in San Diego, California will be finalized for distribution to approximately 65 recipients. Future Section XI meetings will be held May 20-23, 1991 in Orlando, Florida; August 26-29, 1991 in Pittsburgh, Pennsylvania; and November 18-21, 1991 in Anaheim, California. Administrative support will be provided for the activity to develop qualification requirements for the eddy current personnel, equipment, and procedures used for ET/ISI of steam generator tubes.

The proposed new Section V requirements for computerized UT imaging systems will be converted into nonmandatory appendix format and resubmitted for adoption by the SGUT. The concept of developing Code rules under Section T-435 will be reconsidered and possibly deferred pending consensus decisions to be reached by the SGUT during the next two scheduled meetings.

3.0 Pressure Vessel Inspection Task

3.1 Pressure Vessel Inspection

3.1.1 Summary

The objective of this task is to determine the reliability of U.S. ultrasonic inservice inspection of nuclear reactor pressure vessels. This objective is to be accomplished by utilizing data from PISC-II round robin trials, modelling and limited experimental work to supplement areas not adequately addressed by modelling or round robin trials. Comments from the NRC were addressed and a revised document was resubmitted to the NRC in June 1990. Additional comments have been received from the June draft, and these comments are being addressed. A final version of this report will be submitted to the NRC program manager.

3.1.2 Introduction

The pressure vessel inspection task is divided into two subtasks which are:

- **PISC II Re-analysis** - The initial effort in this task is an analysis of data gathered during the PISC-II round robin trials. Ultrasonic inspection data was gathered on four heavy section steel components which included two plates and two nozzles configurations. A total of 45 teams from the Common Market, Japan, and the United States participated in the round robin.

- **RPV Research** - The focus of this activity is to track the work being performed under the PISC III program. This means to ensure that the PISC III work of the Action 2 on Full Scale Vessel Tests (FSV) and the Action 3 on Nozzles and Dissimilar Metal Welds provides useful information for conditions and practices in the USA. We are also tracking the PISC III work and will relay points of interest and any concerns to the NRC that may arise from the analysis of the newly created and evolving data base.

3.1.3 Status of Work Performed

A summary of the work performed for each subtask is provided below.

3.1.3.1 PISC II Re-analysis

A summary of the analysis was provided in semi-annual report NUREG/CR-4469, Vol. 11. No work was performed during this reporting period; we are awaiting NRC comments on the June 1990 draft.

3.1.3.2 RPV Research

The objective of this work is to track the work that is currently being performed under the PISC III program. Of particular interest is the work being conducted in Actions 2 and 3. These actions will provide useful information concerning the capability to inspect nozzles and dissimilar metal welds and begin to address some aspects of the ability of advanced techniques to accurately size flaws and some aspects of the reliability to inspect actual vessels. The initial results from these studies will begin to be made available to the PISC III Management Board in late 1991. At this time, there are no results available; but these studies should provide some very good and useful data bases and conclusions in the near future.

Based on the results and data bases from the PISC III program, deficiencies will be identified and a program to provide the necessary supplemental information will be developed and implemented. But at this time, the activity is simply tracking the PISC III program and the results being developed therein.

3.2 Equipment Interaction Matrix

3.2.1 Summary

The objective of this work is to evaluate the effects of frequency domain equipment interactions and determine tolerance values for improving ultrasonic inspection reliability. An analysis was performed to evaluate frequency domain effects using computer models to calculate the flaw transfer function, and experimental measurements to verify calculated values and determine if various extraneous effects are important.

The primary purpose of the present work is to apply an analysis method developed for thin steel sections to thicker flat sections and to validate the work through limited experimental studies. Also emphasized, were efforts devoted to presenting the work and results obtained in the previous reporting period. Other related activities included:

- Model calculations were performed to determine the sensitivity of 45° and 60° SV pulse-echo results to changes in equipment parameters when thick (6 to 12 inch) steel sections are examined. The results were essentially the same as those found for the thin section inspection model study. The ASME Code requirements for equipment center frequency were again found to be inadequate, as was found for thin sections.

- Results from an experiment performed, in the previous reporting period, to measure the ultrasonic equipment parameter sensitivity and to test model predictions as they affect ASME code requirements were analyzed. These results were consistent with the model, but were not as sensitive to center frequency changes as predicted by the model.

- The most significant results from equipment interaction studies on thin, flat steel sections were presented at the Review of Progress in Quantitative Nondestructive evaluation Conference in July 1990.

- The model's performance was improved by modifying its computer software to run 10 times faster, and making it more useful by backing-up all related software on disks and documenting each element of the program.

- Completed a draft version of the NUREG topical report on the work performed to date.

- Reviewed PISC III modeling paper and made recommendations.

- A presentation was given to the cognizant ASME Section XI Code committees, and a paper was written for the 10th International Conference on NDE in The Nuclear Industry.

3.2.2 Introduction

The goal of this work is to define operating tolerance requirements for UT/ISI equipment that limit the effects of frequency domain interactions, thus, improving ISI reliability. This work will determine the acceptability of equipment specifications in ASME Code Case N-409-1 and Section XI Appendix VIII. The current specifications are based on engineering judgement, rather than an analytical foundation. The Interaction Matrix Study will provide this technical foundation. Both thin sections (piping) and thick steel sections (pressure vessels) are being evaluated.

The following work was completed during previous reporting periods:

- A mathematical model was developed to calculate the transfer functions (frequency responses) of specular reflection from smooth planar defects, and the model was used to identify worst-case defects for frequency domain equipment interactions. A paper on the model was presented at a 1988 conference (Green and Mart 1989).

- Equipment bandwidth and center frequency sensitivity studies were performed for 45° and 60° SV inspection of thin sections (piping) using calculated worst-case flaw transfer functions. The 45° SV inspection was found to be slightly more sensitive to changes in equipment parameters. However, the model indicated (in either case) that the ASME Code requirements for equipment center frequency are inadequate.

3.2.3 Status of Work Performed

Results from an experiment performed, in the previous reporting period, to measure the ultrasonic equipment parameter sensitivity and to test model predictions as they affect ASME Code requirements were analyzed. These results were consistent with the model, but were not as sensitive to center frequency changes as predicted by the model. This is due to necessary simplifications that are built into the model to obtain reasonable run-times, on presently available computer systems. Therefore, the laboratory measurements show the model capable of pinpointing worst-case flaws that can then be examined using the same equipment found in field applications, for inspecting a nuclear power plant.

Model calculations were performed to determine the sensitivity of 45° and 60° SV pulse-echo inspection results to changes in equipment parameters when thick (6 to 12 inch), flat steel sections are examined. The results were essentially the same as those found during the thin section inspection model study. The model accounted for the greater attenuation a signal must experience when passing through a thicker material. The ASME code requirements for equipment center frequency were again found to be inadequate, just as for thin sections.

The most significant results from equipment interaction studies on thin, flat steel sections were presented at the Review of Progress in Quantitative Nondestructive Evaluation Conference in July 1990. This work was entitled "The Effect of Equipment Bandwidth and Center Frequency changes on Ultrasonic Inspection Reliability: Are Model Results Too Conservative?". A summary will appear in *Review of Progress in Quantitative Nondestructive Evaluation*, Vol. 10B.

3.2.4 Future Work

The following work remains to be completed:

- Expand the flaw model to include curved sections (nozzles) and perform equipment parameter sensitivity studies for thick sections (reactor pressure vessels).
- Verify curved surface model calculations experimentally.
- Report findings from curved section study to the NRC and the cognizant ASME Code committees.
- Extrapolate results from curved surface study to other important surface geometries.

4.0 New Inspection Criteria Task

4.1 Summary

Work continued on assessments of the adequacy of existing ASME Code requirements for ISI and on developing technical bases for improved ISI requirements that will assure high nuclear power plant component structural integrity. Development of a comprehensive probabilistic approach for improved inspection requirements moved forward. A major focus of this effort has continued to be participation in an ASME Research Task Force on Risk-Based Inspection Guidelines.

Calculations during this reporting period have applied probabilistic risk assessment (PRA) to establish inspection priorities for pressure boundary systems and components. Plant-specific risk-based studies have been conducted for the Surry Unit 1 Nuclear Power Station. This effort is being performed with the cooperation of Virginia Electric Power Company, and involved two additional plant visits during this reporting period for system walkdowns and detailed interviews with plant staff. Estimates of failure probabilities have been an important input to the risk-based calculations for Surry-1. Data from an expert judgement elicitation performed in May of 1990 have been analyzed to estimate rupture probabilities for components in four critical systems (reactor pressure vessel, reactor coolant system, low pressure injection system and auxiliary feedwater system). A preliminary ranking of components in these four systems for ISI prioritization has been completed.

4.2 Introduction

This task is directed to the development of improved inservice inspection (ISI) criteria using risk-based methods, with the long-range goal to propose changes for consideration by ASME Section XI Code. These improved criteria will help to establish priorities for selecting systems, components, and structural elements for inspection, and will help to determine the location, extent, frequency, and method of examination. The objective is to ensure that ISI programs ensure a suitably low component failure probability, and thus contribute to safe nuclear power plant operation.

In past work, we have reviewed and evaluated various concepts for probabilistic inspection criteria, and have interacted with other industry efforts, notably through a newly organized ASME Research Task Force on Risk-Based Inspection Guidelines. During FY89 we completed pilot applications of PRA methods to the inspection of piping, vessels, and related components for a sample of eight representative nuclear power plants (Surry-1, Zion-1, Sequoyah-1, Oconee-3, Crystal River-3, Calvert Cliffs-1, Peach Bottom-2 and Grand Gulf-1). The results of this study can be found in Vo et. al. 1990. In summary, the results provided generic insights that could be extrapolated from the eight plants to specific classes of light water reactors. While a few exceptions were noted, the PRA-based priorities for inspection of systems were generally correlated with current ASME Section XI requirements for Class 1, 2, and 3 systems.

In FY90 our work addressed inspection priorities at the more detailed component level, and focused on plant-specific calculations for the Surry Unit 1 Nuclear Power Station. During this reporting period we have continued with the Surry-1 studies, both for the systems previously selected for detailed study and for additional systems that will give a more complete picture of the most risk significant components within the plant. Results of recent work are described below.

4.3 Status of Work Performed

4.3.1 ASME Task Force on Risk-Based Inspection Guidelines

During this reporting period we have continued to develop approaches for risk-based inspection requirements. Activities in this area have involved active PNL participation on a special ASME Research Task Force on Risk-Based Inspection Guidelines. The ASME group has been identified by PNL as an effective route to achieve long-range goals for improved inspection criteria. The initial focus of the ASME Task Force has been on nuclear power applications, and on the development of practical recommendations for use of risk-based methods that can be recommended for consideration by ASME Section XI Code.

There were two meetings of the ASME Research Task Force during this reporting period as follows:

- December 10-12, 1990 at Anaheim, California

- February 5-7, 1991 at San Diego, California

The Phase I work of the Task Force has produced a general document that recommends and describes appropriate methods for establishing inspection guidelines using risk-based approaches for any facility or structural system. A draft of this document was revised during this reporting period to address comments from a peer review process, and is scheduled for publication by ASME during May of 1991.

Completion of a second draft document on the special topic of nuclear power applications was accomplished during this reporting period (Volume 2 - Part 1) (ASME Research Task Force on Risk-Based Inspection Guidelines, 1992). This document recommends and describes specific methods to be used in developing risk-based inspection plans for nuclear power facilities.

Future efforts of the ASME Research Task Force will apply the recommended risk-based methodologies to develop improved inspection programs for nuclear power plant components (Volume 2 - Part 2). This work will be summarized in a document which is scheduled for publication in the later part of 1993. The document will make recommendations for consideration by ASME Section XI Code.

4.3.2 Plant Specific PRA Application to Surry-1

A major part on this task involves the application of existing probabilistic risk assessments (PRA) to establish inspection priorities for pressure boundary systems and components. During this reporting period a pilot application of PRA methods to the Surry-1 plant continued forward.

The Surry-1 work has applied a methodology (Vo et al. 1989) that uses the results of PRA's in combination with the techniques of failure modes and effects analysis (FMEA) to identify and prioritize the most risk-important systems and components at nuclear power plants. The specific systems initially selected for analysis were the reactor pressure vessel, the reactor coolant, the low pressure injection (including the accumulators) and the auxiliary feedwater. Efforts during this reporting period have been expanded to address other systems including the high pressure injection, main feedwater, service water, component cooling water, main steam, condensate, and residual heat removal systems.

Core damage frequency (Level-I PRA) has been used in this study as the bottom line risk measure. FMEA results are applied to calculate the relative importance of each component within the systems being addressed. The calculated importance measures reflect the expected consequences of failure of the component (from the Surry-1 PRA) and the expected probability of failure (rupture) of the component. Estimates of rupture probabilities for the Surry-1 components have been obtained from an expert judgement elicitation.

Staff from the Virginia Electric Power Company (VEPCO) have been actively participating in the pilot study. This participation is important to assure that the plant models are as realistic as possible and reflect plant operational practices. Two visits to the Surry-1 plant were made during this reporting period: 1) the week of November 12th for system walkdowns, and 2) the week of March 18th for discussions with plant operational technical staff.

Table 4.1 shows a preliminary numerical ranking of the relative risk-importance of components within the selected Surry-1 systems (stated in terms of core damage frequency). On the basis of core damage frequency, the most risk-important components are those located within the beltline region of the reactor pressure vessel. Relatively high rankings were estimated for certain pipe segments of the low pressure injection (LPI) system, and also certain pipe segments within the auxiliary feedwater system. Potential ruptures of other components had much smaller contributions to core damage frequency, with the calculated risk importances covering a range of over eight orders of magnitude in numerical values.

Table 4.1. Preliminary Risk Important Components for Selected Systems at Surry 1

System - Component	Core Damage Frequency	Rank
RPV - Beltline Region	1.89E-06	1
RPV - Bottom/Lower Head	7.82E-08	2
RPV - Upper Shell/Head	6.68E-08	3
LPI - HL Discharge Header to Isolation Valves	5.26E-08	4
LPI - CL Discharge Header to Isolation Valves	4.68E-08	5
LPI - ACC Isolation Valve to RCS	4.68E-08	6
LPI - Supply Lines/Pump Suction Sources	3.79E-08	7
LPI - Isolation Valve to RCS Cold Leg	2.31E-08	8
AFW - Supply Lines/Pump Suction Sources	8.64E-09	9
AFW - Isolation Valve to SG	7.52E-09	10
LPI - Isolation Valve to RCS Hot Leg	5.72E-09	11
AFW - Discharge Header to Isolation Valves	3.73E-09	12
AFW - MS Line to Turbine Drive for AFWTDP	2.10E-09	13
RCS - Pressurizer Spray Line	1.01E-09	14
RPV - Nozzle to Vessel Welds	2.08E-10	15
RPV - Vessel Studs	5.00E-11	16
RPV - Nozzle Forging Inlet/Outlet	3.00E-11	17
RCS - Pressurizer Relief Line	2.26E-12	18
RCS - Reactor Coolant Loop	1.96E-12	19
RCS - Pressurizer Surge Line	9.15E-13	20
LPI - ACC Suction Line	6.33E-14	21
LPI - ACC Sample Line	5.36E-14	22
LPI - ACC Discharge Line	2.92E-14	23

RVP = Reactor Pressure Vessel
LPI = Low Pressure Injection
AFW = Auxiliary Feedwater
RCS = Reactor Coolant System
ACC = Accumulators

MS = Main Steam
SG = Steam Generator
HL = Hot Leg
CL = Cold Leg

In future work the results of Table 4.1 will be further quantified with refined inputs to the FMEA calculations. Indirect effects of component ruptures will be incorporated into the evaluation. Additional systems will also be evaluated to give a comprehensive ranking of all the most important components within the Surry-1 plant systems that should be addressed when assigning the priorities for inservice inspection. These risk-based priorities can then be compared with current inservice inspection requirements as specified by Section XI of the ASME Code. The objective is to identify if and what needed improvements are required to current ISI plans. These results will be made available to the ASME Research Task Force as recommendations for consideration by ASME Section XI.

4.3.3 Expert Judgement Elicitation for Rupture Probabilities

The risk-based studies of the Surry-1 plant have required estimates of rupture probabilities on a detailed component-by-component level. Because neither sufficient data from operating experience nor detailed fracture mechanics analyses are available, the expert judgment elicitation process has been selected as a method to estimate needed rupture probabilities.

PNL conducted an expert judgment elicitation meeting on May 8-10, 1990 at Rockville, Maryland to address the issue of failure probabilities. The goal was to obtain numerical estimates for probabilities of catastrophic or disruptive failures in pressure boundary systems and components in pressurized water reactors (PWRs). The systems addressed by the May 1990 elicitation were the reactor pressure vessel, reactor coolant, low pressure injection (including the accumulators), and auxiliary feedwater.

The expert elicitation was performed using a systematic procedure, which closely followed the approach used for the NUREG-1150 PRAs (NRC 1990 and Wheeler et al. 1989). During this reporting period the results of the elicitation were compiled into distributions by PNL staff. The distributions determined a "best" estimate of rupture probability for every component present in the data set.

Figure 4.1 through 4.5 show failure probability estimates for components within the selected systems at Surry 1. These plots represent the distributions of estimated failure (rupture) probabilities provided by the various experts. An individual plot graphically displays the following features of the distribution :

1. The "whiskers" identify the extreme upper and lower values of the distribution.

2. The box itself locates the 25% and 75% quantiles (i.e., quartiles) of the distribution. In other words, 50% of the data points will lie within the box.

3. The line within the box intersecting the circle or dot is the median of the distribution.

For all the systems selected for the study, plots show that failure probability estimates vary between 1.0E-09 to 1.0E-03 failures/year, depending on the systems, components within the systems, and component locations. The component medians generally vary within a factor of 10 for a given system.

Significant trends in estimated rupture probabilities for specific systems include:

- For the reactor pressure vessel (Figure 4.1), the highest probabilities are for penetrations to the vessel heads (e.g., instrument lines and control rod drive mechanisms). High probabilities are also estimated for the embrittled welds of the vessel beltline region.

- For the auxiliary feedwater system (Figure 4.2), the highest failure probabilities are for the piping segments extending from the containment isolation valves to the steam generators. Factors contributing to these potential failures are corrosion, water hammer events and thermal stratification.

- For the low pressure injection system (Figure 4.3), the highest failure probabilities are for the piping segments that inject into the cold and hot legs of the reactor coolant system loops. Factors contributing to these potential failures are thermal stresses resulting from valve leakage and potential overpressurization due to inadvertent actuation of safety system injection.

- For the accumulators (Figure 4.4), the highest failure probabilities are for the discharge headers extending from the second isolation valves to the reactor coolant system loops. Factors contributing to these potential failures include thermal stresses resulting from valve leakage and evidence of water hammer events.

- For the reactor coolant system (Figure 4.5) the highest failure probabilities are for the pressurizer spray lines. Factors contributing to these potential failures include sensitized piping (at Surry 1) and cyclic thermal stresses.

In summary, the expert elicitation produced a set of component rupture probabilities for various components within the selected systems at Surry 1. In addition, information from the expert judgment elicitation and access to utility staff greatly enhanced the realism and credibility of the Surry plant analyses.

4.4 Future Work

Future activities on the New Inspection Criteria Task will include:

- Continuing support of the ASME Research Task Force on Risk-Based Inspection Guidelines.
- Expert elicitation for rupture probabilities on the remaining systems at Surry 1.
- Complete the ISI prioritization for components at Surry 1.

The long range objective will be to develop improved criteria for inservice inspections (what, where, when, and by what method) using risk-based methods. The pilot calculations serve to demonstrate the feasibility of the proposed approach, and will focus on the component level to establish inspection priorities. Other calculations will be used in the development of risk-based inspection programs for the high priority components. These inspection programs will make use of information on the probabilities and consequences of component failures to assign target values of probabilities that are to be maintained by inservice inspection. Probabilistic fracture mechanics and decision analysis methods will identify inspection strategies that meet criteria for both safety and cost effectiveness. Output from the New Criteria Task will be made available to the ASME Research Task Force on Risk-Based Inspection Guidelines for their use in preparing a document that will recommend risk-based inspection programs for codes and standards consideration.

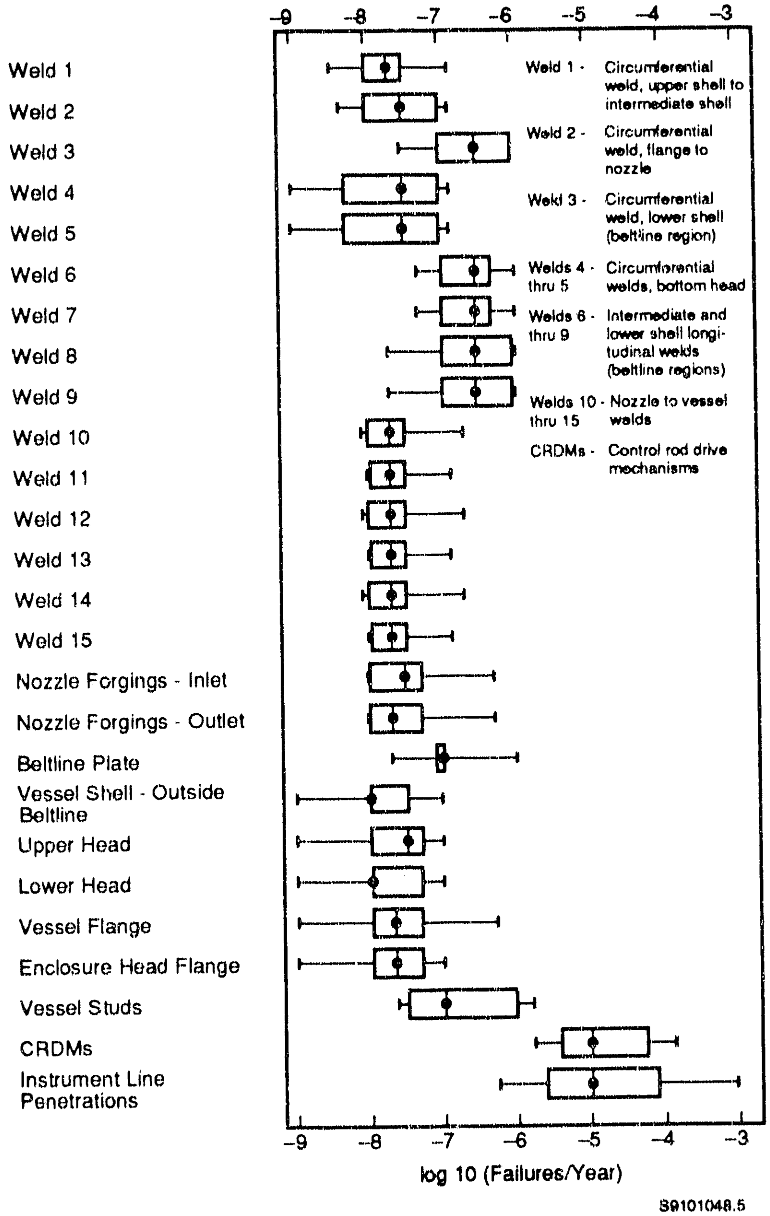

Figure 4.1. Failure Probability Estimates for the Reactor Pressure Vessel Components

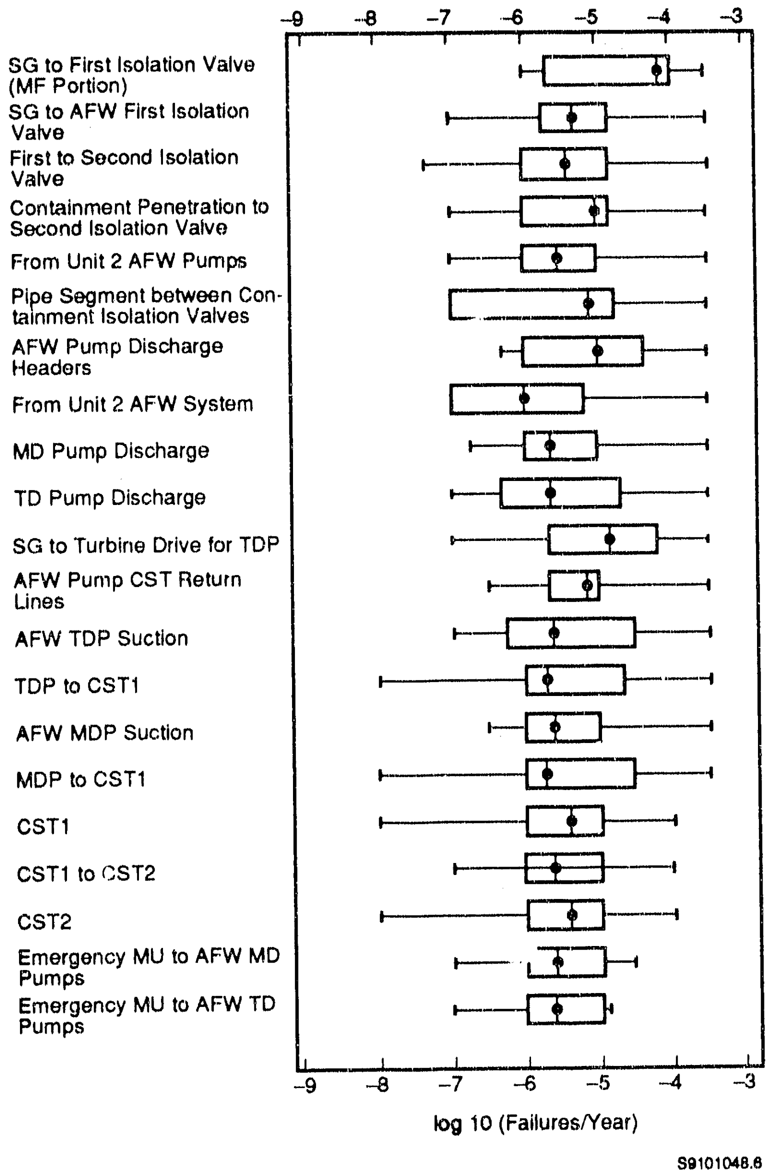

Figure 4.2. Failure Probability Estimates for the Auxiliary Feedwater System Components

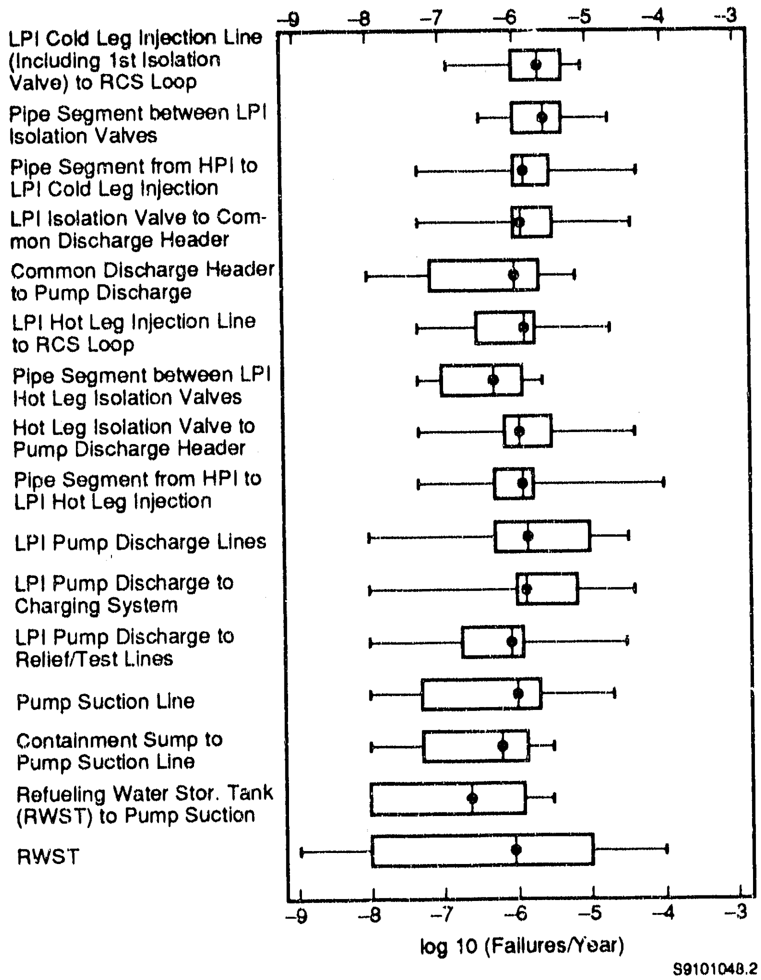

Figure 4.3. Failure Probability Estimates for the Low Pressure Injection System Components

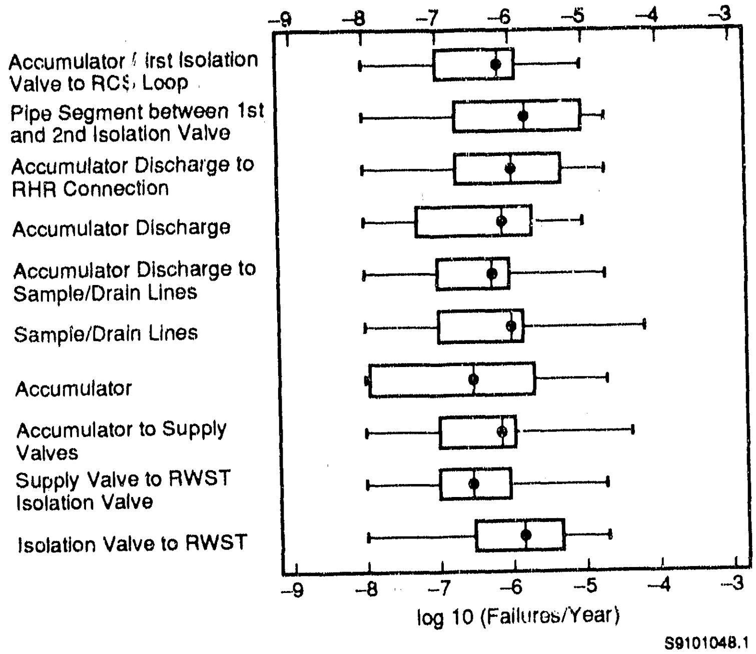

Figure 4.4. Failure Probability Estimates for the Accumulator System Components

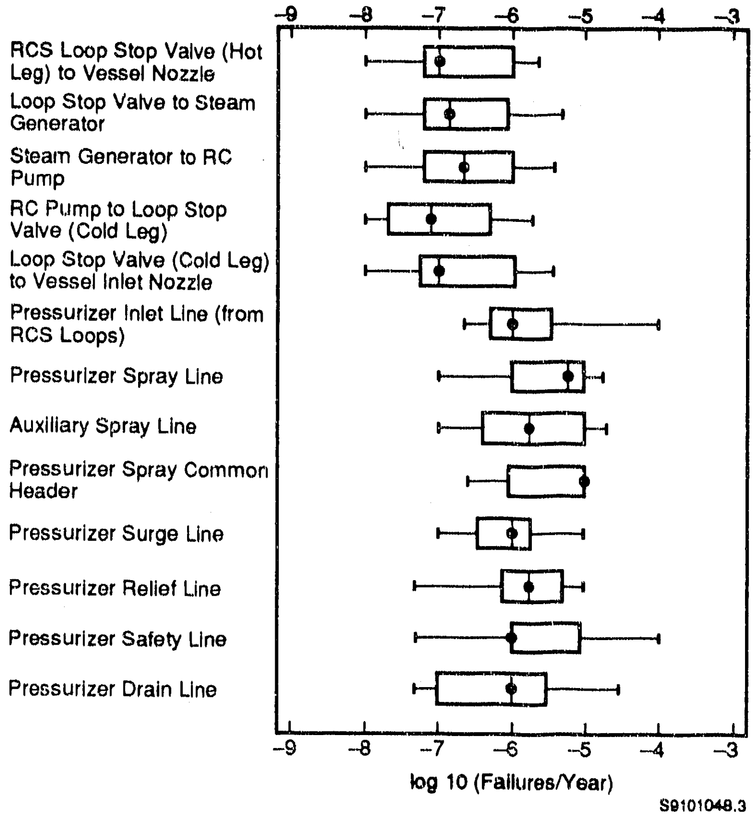

Figure 4.5. Failure Probability Estimates for the Reactor Coolant System Components

5.0 Consult on Field Problems

5.1 Introduction and Summary

The objective of this work is to provide a rapid response to urgent and unexpected problems as they are identified by the Office of Nuclear Regulatory Research (RES). There was no activity under this task during this reporting period.

5.2 Status of Work Performed

No work performed during this reporting period.

5.3 Future Work

Since this task is consciously designed as a mechanism for responding to urgent and/or unexpected needs and requests from RES, it is not possible to plan or describe the specific work activities that might occur during the next reporting period.

6.0 Piping Inspection Task

This task is designed to address the NDT problems associated with the reliable inspection of piping used in light water reactors. The primary thrust of the work has been on wrought and cast stainless steel since these materials are harder to inspect than carbon steel. However, many of the subtasks' results also pertain to carbon steel. The current subtasks are: cast stainless steel inspection, surface roughness, field pipe characterization, and PISC-III activities.

The work accomplished during this reporting period is summarized in the following paragraphs:

- Cast Stainless Steel Inspection - The objective of this subtask is to evaluate the effectiveness and reliability of ultrasonic inspection of cast materials within the primary pressure boundary of LWRs. Activities for this reporting period included microstructural classification of CCSS material within the PISC NDW Assembly 25 block, use of the Rayleigh critical angle technique to characterize CCSS microstructure, a draft of a cooperative work effort between NRC (PNL) and UKAEA, a paper on phase mapping of ultrasonic fields in CCSS, and preparation of a white paper proposing the use of adaptive ultrasonics to compensate for distortion caused by cast grain structures.

- Surface Roughness. The objective of this work was to establish specifications such that an effective and reliable ultrasonic inspection is not precluded by the condition of the surface from which the inspection is conducted. Activities for this reporting period included further refinement of the model by CNDE and development of better experimental procedures by PNL for obtaining quantitative data to compare with model predictions.

- Field Pipe Characterization - The objective of this subtask is to provide pipe weld specimens that can be used for studies to evaluate the effectiveness and reliability of ultrasonic inservice inspection (UT/ISI) performed on BWR piping. Documentation of the five safe-ends removed from the Monticello nuclear power station are no longer needed for any programmatic work. Processes to dispose of these samples are under review to meet the new requirements for disposal required by state and federal agencies.

- PISC-III Activities - This activity involves participation in the PISC-III program to ensure that the work addresses NDE reliability problems for materials and ISI practices on U.S. LWRs. This includes support for the co-leader of Action 4 on Austenitic Steel Tests (AST); coordination of participation by U.S. teams on various Actions; and input to the studies on human reliability, specimens for use in the Parametric, Capability, and Reliability studies of the AST, following work being performed under Action 2 on Full-Scale Vessel Tests (FSV), Action 3 on Nozzles and Dissimilar Metal Welds, and also tracking the PISC-III work and relaying points of interest and concerns to the NRC that may arise from the analysis of the newly created and evolving data base.

6.1 Cast Stainless Steel Inspection

6.1.1 Introduction

The objective of this task is to evaluate the effectiveness and reliability of ultrasonic inspection of cast materials used within the primary pressure boundary of LWRs. Due to the coarse microstructure of this material, many inspection problems exist and are common to structures such as cladded pipe, inner-surface cladding of pressure vessels, statically cast elbows, statically cast pump bowls, centrifugally cast stainless steel (CCSS) piping, dissimilar metal welds, and weld-overlay-repaired pipe joints. Far-side weld inspection is included in the work scope since the ultrasonic beam passes through weld material.

CCSS piping is used in the primary reactor coolant loop piping of 27 pressurized water reactors (PWRs) manufactured by the Westinghouse Electric Corporation. However, CCSS inspection procedures continue to perform unsatisfactorily due to the coarse microstructure that characterizes this material. The major microstructural classifications are a columnar, and equiaxed, and a mixed columnar-equiaxed microstructure of which the majority of field material is believed to be the latter.

6.1.2 Summary

Activities for this reporting period included microstructural classification of CCSS material within the PISC III Nozzle and Dissimilar Metal Welds (NDW) Assembly 25, use of the Rayleigh critical angle technique to characterize CCSS microstructure, draft input to a cooperative work effort between NRC (PNL) and UKAEA, a paper on phase mapping of ultrasonic fields in CCSS, and preparation of a white paper proposing the use of adaptive ultrasonics to compensate for distortion caused by cast grain structures.

6.1.3 Status of Work Performed

Activities for this work period included microstructural classification of CCSS material within a PISC III (Programme for Inspection of Steel Components) block, use of the Rayleigh critical angle technique to characterize CCSS microstructure, draft input to a cooperative work effort between NRC (PNL) and UKAEA, a paper on phase mapping of ultrasonic fields in CCSS, and a white paper which proposed the use of adaptive ultrasonics to compensate for distortion caused by cast materials (see Appendix A).

A paper was submitted for publication in the proceedings to the annual "Review of Progress in Quantitative Nondestructive Evaluation" conference. The paper was entitled "Phase Mapping of Ultrasonic Fields Passed through Centrifugally Cast Stainless Steel." The primary conclusion of this work was that the fringe pattern for longitudinal waves at 1 and 2 MHz displayed significantly less distortion than was expected. A suggestion for future work was to evaluate phase data for flaw detection and image enhancement by compensating for phase distortion (see Appendix B).

An opportunity became available in October 1989 to classify CCSS microstructure contained within PISC III NDW Assembly 25. This assembly was en route from Southwest Research Institute (SwRI) in San Antonio, Texas to France, and personnel and instrumentation were transported to SwRI since it was more economical than shipping the block to PNL. In preparation for the trip, personnel at PNL attempted the techniques defined by Kupperman, et. al. (1987) for ultrasonically characterizing cast stainless steel. Data, analysis, and conclusions were then included in a draft letter report that was submitted to the NRC Program Manager, and later provided to the Ispra Research Center. Data was requested on the microstructural classification of the material when destructive tests are performed at the Ispra Research Center.

The principal conclusion was that the longitudinal wave velocity of the CCSS was consistently measured to be within 2.5 percent of the value for columnar material. Therefore, a high probability was given that the material is a pure columnar microstructure. It was found that this technique cannot be employed in the field because it requires a greater accuracy of through-wall thickness than can be effectively determined by nondestructive means (see Appendix C).

Work began in January 1990 to evaluate the Rayleigh critical angle technique as a means of classifying cast stainless steel microstructure. The premise was that different groupings of anisotropic grains may be characterized by wave velocity and that either amplitude or phase images would correlate with material-property changes. The evaluation required modification of a scanning system to permit mplitude and phase measurements, a pitch-catch transducer configuration, and use of multi-frequencies to probe anterior layers of different thicknesses. The transmitter and receiver were inclined at equal angles opposite each other with the respective beams overlapping at the insonicated area. The selected angle was the critical angle typical of the material being investigated.

Results were encouraging in that images displaying texture were acquired from samples having unique microstructures. C-scan images were made at 1.0, 0.5, and 0.25 MHz for each of the three samples with near-surface wave velocity of the material modulating the received signal amplitude. Since penetration is inversely proportional to frequency, changes in wave velocity and, hence, microstructure were detected respectively for layer thicknesses of 3, 6, and 13 mm. The three samples were a pure equiaxed, a pure columnar, and a layered columnar-equiaxed microstructure. The mixed-mode sample had a columnar outer surface that transformed into an equiaxed layer at a depth of about 10 mm. Detection of this transformation was considered to be a primary goal since it would demonstrate that the technique is capable of detecting changes in microstructure as a function of depth.

Results from the Rayleigh critical angle work were incorporated into a NUREG/CR report and also submitted as an abstract to the annual "Review of Progress in Quantitative Nondestructive Evaluation" conference. The primary conclusion was that encouraging results were obtained; however, insufficient data existed to state that microstructural classification of the entire pipe wall was possible.

The Rayleigh critical angle work was also reported at the annual Light Water Reactor conference. After the presentation, personnel from UKAEA suggested that a cooperative work effort on cast material be started between NRC (PNL) and UKAEA. A draft work plan was prepared and sent to the NRC. Several iterations of the plan are expected before obtaining mutual approval by the NRC, PNL, and UKAEA.

6.1.4 Future Work

Work will focus on collecting all the pertinent PNL information concerning CCSS and presenting this at a workshop for NRC personnel. This will include the CCSSRRT, selective frequency filtering of ultrasonic signals for CCSS microstructures, ultrasonic field distortion, and ultrasonic attenuation. Additional critical angle work will be performed to determine how this technique might be implemented in the field. Specifically this would consist of implementing much lower frequencies; e.g., 25 to 30 kHz and classifying each layer as penetration is increased. The low frequency is required so that penetration to the inner diametrical surface is accomplished. Prior to performing experimental work, an analysis will be performed to assure that successive layers in depth can be classified. CCSS work will also continue to document microstructures, acquire ultrasonic attenuation measurements from the respective microstructures, and acquire ultrasonic field maps from complex material microstructures. Far-side inspection and dissimilar metal welds work will include sample acquisition and metallography, and the acquisition of ultrasonic field maps to document field distortion.

6.2 Surface Roughness Conditions

6.2.1 Summary

The objective of this work was to establish specifications such that an effective and reliable ultrasonic inspection is not precluded by the condition of the surface from which the inspection is conducted. Activities for this reporting period included further refinement of the model by CNDE and development of better experimental procedures by PNL for obtaining quantitative data to compare with model predictions. Delays occurred in model refinement due to funding problems for CNDE.

6.2.2 Introduction

Past efforts included an attempt to quantify the effect produced by an outer surface irregularity on the UT response from a 10% machined notch. This approach was then redefined to cooperate with EPRI in establishing a mathematical model to be used as an engineering tool for deriving guidelines for surface specifications. Under the auspices of the cooperative agreement, the Center for NDE (CNDE) at Ames Laboratory with EPRI funding was assigned the task of refining an existing, isotropic model and PNL with NRC funding was assigned the task of acquiring experimental data to support model refinement and validating the model.

6.2.3 Status of Work Performed

Activities for the past work period included continued refine·:ent of the model by CNDE, and development of better experimental procedures by PNL for obtaining quantitative data for comparing to the model predictions. Delays occurred in model refinement due to funding cuts at EPRI. However, work continued at CNDE.

Dr. R. B. Thompson and Mr. A. Minachi of the CNDE have been refining the model. Their work has included writing subroutines to determine the normal vector to the phase front after it had passed across the interface, and new Gauss-Hermite polynomials for the wave in the vicinity of the interface by means of a numerical integral calculation. The important issue here was the speed of convergence. Mr. Minachi stated that subroutines already exist for determining the wave at a selected distance from the interface by using the new polynomials and that this model version will predict the single frequency response of a wave transmitted across an interface.

6.2.4 Future Work

The schedule of model refinement, delivery of the model to PNL, model validation by PNL, and use of the model to determine code recommendations for surface condition is being redefined. If a reasonable schedule cannot be established, then the simpler two-dimensional model already at PNL might be used instead of the three-dimensional model that would have been obtained from CNDE. A tentative delivery date to PNL of a first version of the model was established as August 1991.

6.3 Field Pipe Characterization

6.3.1 Introduction

The objective of this subtask is to provide pipe weld specimens for studies to evaluate the effectiveness and reliability of ultrasonic inservice inspection (UT/ISI) performed on BWR piping. Documentation of the five safe-ends removed from the Monticello nuclear power station was reviewed and an extensive data package was assembled to accompany shipment of these specimens to Joint Research Centre, Ispra, Italy. However, PISC-III representatives decided that evaluation of removed-from-service components could no longer be supported by the PISC-III program. Processes to dispose of these samples are under review.

6.3.2 Status of Work Performed

It became official during this reporting period, by vote of the PISC-III Management Board, that removed-from-service components would no longer be supported by the PISC III program. As a result, these specimen will have to be buried. The new rules and regulations from the Environmental Protection Agency make this process more difficult and confusing because the rules are not clearly stated and there seems to be a wide range of interpretations of how to meet the requirements. We have begun to try to unravel this complex and confusing set of requirements.

6.3.3 Future Work

Proceed with determining what must be done to meet requirements in order to bury the five safe-ends.

6.4 PISC-III Activities

6.4.1 Introduction

The objective of this subtask is to contribute to the international Programme for the Inspection of Steel Components III (PISC III) to facilitate current studies on the reliability, capability, and parametric analysis of NDE techniques, procedures, and applications. This includes full-scale vessel testing; piping inspections; and human reliability, real components, nozzles and dissimilar metal welds, and modeling studies on ultrasonic interactions. These data will be used in quantifying the inspection reliability of ultrasonic procedures and the sources and extent of errors impacting reliability.

The primary areas in which PNL participated include Action No. 1 on Real Contaminated Structures Tests (RCS), Action No. 2 on Full-Scale Vessel Tests (FSV), Action No. 3 on Nozzles and Dissimilar Metals Welds (NDM), Action No. 4 on Round-Robin Tests on Austenitic Steels (AST), Action No. 6 on Ultrasonic Testing Modeling (MOD), and Action No. 7 on Human Reliability Exercises (REL). These actions are being followed to ensure that conditions, materials, and practices in the U.S. are being included in the work so that the results are transferable to the U.S.

6.4.2 Status of Work Performed

The primary activities that occurred this reporting period included the participation in a PISC III Management Board meeting, coordination of U.S. teams that participated in the PISC III Action 3, and work to try to get teams form the U. S. to participate in the Action 4 studies.

The PISC-III Actions are moving forward in terms of the specimens being prepared for circulation. It is apparent that the next few years are going to be very intensive with regard to teams conducting inspections of these assemblies. There will need to be a large effort to get teams from the USA involved in the AST studies.

If these teams are not forthcoming, it will be necessary to determine if it is possible to provide some type of financial support to gain participation. This is not an acute problem at this time, but will be so in the next 6 to 9 months.

The specimens for both the cast-to-cast and the cast-to-wrought studies have not been fabricated, but they are on a schedule for completion in the late spring of 1992. At that time, they should start circulation, and this will most likely being in Europe.

6.4.3 Future Work

Future work will include attending future PISC III Management Board meetings, further coordination of teams from the U.S. for the AST and involvement in the data analysis of the data from the AST.

7.0 References

ASME Research Task Force on Risk-Based Inspection Guidelines, "Risk-Based Inspection - Development of Guidelines, Volume 2 - Part 1, Light Water Reactor Nuclear Power Plant Components," CRTD-Vol. 2-2, American Society of Mechanical Engineers, New York, 1992.

Kupperman, D. S., K. J. Reimann, and J. Abrego-Lopez, "Ultrasonic NDE of Cast Stainless Steel" in NDT International, Vol. 20, No. 3, pp. 145-142, 1987.

U.S. Nuclear Regulatory Commission (NRC), NUREG-1150, "Severe Accident Risks: An Assessment for Five U. S. Nuclear Power Plants, Final Summary," Vol. 1, Nuclear Regulatory Commission, Washington, D.C., 1990.

Vo, T. V., B. F. Gore, L. J. Eshbach, and F. A. Simonen, "Probabilistic Risk Assessment-Based Guidance for Piping Inservice Inspection." Nuclear Technology, Volume 88 (1), American Nuclear Society, La Grange Park, Illinois, 1989.

Wheeler, T. A., S. C. Hora, W. R. Cramond, and S. D. Unwin, NUREG/CR-4550, "Analysis of Core Damage Frequency from Internal Events: Expert Judgment Elicitation," Vol. 2, Sandia National Laboratories, Albuquerque, New Mexico, 1989.

Appendix A: Adaptive Ultrasonics

by

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ADAPTIVE ULTRASONICS

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INTRODUCTION

Over the last 10-20 years, great progress has been made in the area of adaptive optics. This progress was driven by two basic needs. The first need arose in the military arena, when optical weaponry was being considered. The high power optical beam had a tendency to break up because of the continuously varying atmosphere. The second need arose from the astronomer's frustration in trying to get high resolution images through the atmosphere. Both motivations resulted in a great deal of research into adaptive optics, arriving at remarkably similar solutions.

Ultrasonics suffers from similar problems when the material under consideration is non-homogeneous and anisotropic. Although the distortion is fixed in time and space, unlike the atmosphere which varies in time and space, when the transducer is scanned, the result is the same. Hence, any solutions arrived at in the optical domain are readily transferred to the nondestructive testing (NDT) arena. This white paper summarizes the adaptive optics literature and describes how it may be transferred to ultrasonic inspection.

DISCUSSION

Active or adaptive optical systems are those in which real-time control over optical wavefronts is employed to optimize system performance in the presence of random disturbances. An active optical system is usually comprised of a segmented or deformable mirror which is controlled in such a way as to produce a wavefront that compensates for the distortion imposed on the optical beam. This requires a wavefront sensor to determine what compensation is required, and a control system to alter the shape of the mirror.

This is quite a stretch in thinking for an optical engineer, who must deal with the exceedingly high optical frequencies, and lack of electronics at these frequencies. By contrast, in the low frequency regime of ultrasonics, it is very easy to fabricate electronics for shaping a wavefront via a phased array. Once again, as in holography, it is the optical scientist who made the seminal advances which the NDT engineer can now acquire.

Figure 1 shows four basic adaptive optical systems--two for active and two for passive use. The two block diagrams on the left represent transmitted wavefront systems in which the objective is to maximize the power density on the target. The blocks on the right are designed to optimize the image of a distant object received through a turbulent atmosphere.

The former usually operate at a single wavelength, using radiation generated by a laser. In the ***phase conjugation*** approach, the beam initially reaching the target gives rise to reflection from small areas producing glints which generate spherical waves. These reflected waves traverse the propagation path in the reverse direction and consequently are spatially modified by the turbulence in the same way as the transmitted beam. The received wave is compared with a locally generated reference wave in the wavefront detector and the required correction, which is the phase conjugate of the measured wavefront distortion, is computed in the wavefront processor. A command is then sent to the wavefront modifying device to implement the required correction in the transmitted wavefront. The predistortion impressed on the outgoing wavefront then precisely compensates for the distortion in the propagation path so that the wavefront arriving at the target has the desired spherical shape to maximize the power density at the original glint.

The second transmitted wavefront system is the ***aperture tagging*** approach in which trial perturbations are made in the outgoing wavefront and the optical power returned from a glint at the target is analyzed to determine which perturbations increase the power density. These perturbations are added to the wavefront, and the process continues iteratively until the power density is optimized. There are two basic methods of tagging the perturbations--frequency multidither and sequential or polystep dither. In frequency multidither, the perturbation consists of an ensemble of sine waves at different frequencies, while in the sequential system, the perturbations consist of step changes made consecutively on a fixed time schedule.

In the received wavefront system, the objects viewed are generally self-luminous, producing incoherent radiation over a wide spectral band. The first of these techniques is known as ***wavefront compensation*** and is analogous to the phase conjugation approach in laser transmission systems. The object being viewed may be regarded as a collection of unresolved point sources, each one generating a spherical wave, which is distorted in its passage through atmosphere. After collection by the telescope aperture and passing through the wavefront modifier (assumed to be initially nulled), the distorted wavefront is split in intensity and a portion is sent to the wavefront detector to be analyzed in terms of the local deviation or tilt from the ideal spherical wave. In this way, a complete error map of the received wavefront is generated. The required correction is then computed in the wavefront processor, and the necessary control signals for each local area of the aperture are sent to the wavefront modifier. The wavefront error is consequently nulled at the input to the wavefront detector, so that the optical beam reaching the image detector is essentially diffraction limited.

The ***image sharpening*** technique uses an approach analogous to aperture tagging. Trial perturbations are made in the received wavefront, and the effect is judged by means of a detector located in the image plane, the criterion being to maximize image sharpness using some related quantity such as the integral over the image plane of the square of the image intensity. This is an indirect technique in that some way of reliably distinguishing or tagging the individual aperture perturbations is required.

The actual performance of all these active systems depends on such factors as the error in the wavefront measurement process, the response time of the servo loop in relation to the time constant of the disturbances, and the spatial resolution of the wavefront corrector.

Ultrasonic inspection systems are always of the transmitted wavefront variety. In a general inspection, a collimated or focused transducer is scanned in a two-dimensional pattern, and echoes recorded and displayed in a variety of formats. Any flaws or reflectors within the material will return larger echoes than the surrounding material. Thus, a plot of the returned waveform as a function of (x, y, t) takes on the aspects of an image. The desired result is an estimate of the position, size, and shape of the flaw.

In order to achieve the goal stated above, the interrogating ultrasonic beam should be well defined so that the echo can be accurately located in space. This is readily achievable in most structural materials, such as aluminum and steel. There are, however, some materials with large grain structures, such as cast stainless steel (CSS), that distort the ultrasonic beam because of significant velocity variations from grain to grain. When this occurs, it is not possible to locate the echo with any great accuracy, because as the transducer is scanned, the ultrasonic beam encounters a different grain structure. This effectively dislocates and deteriorates the beam from moment to moment, very much like the atmosphere perturbs an optical beam.

It would seem that solutions arrived at in optics could be applied to ultrasonics to allow CCS materials to be inspected. It is also obvious that the NDE problem most closely resembles the transmitted wavefront system illustrated in Figure 1(a) and (b). We will illustrate these two techniques using only a two-element transducer. Consider Figure 2, where the transducer has only two segments, and the objective is to project a collimated beam through a material having two propagation velocities, one for each segment.

Initially, the phase shifter is nulled, so that the two elements act as a single transducer emitting a plane wave. As the wave propagates, the wavefront develops a discontinuity because each element sees a different propagation velocity. Upon refection and propagating back through the material, the wavefront becomes even more distorted. If the signals received at the two elements are simply summed, the result would be:

$$s(t) = [2(1+\cos\theta)]^{1/2} \exp j[\omega_0 t+\theta/2] \qquad (1)$$

where θ = phase shift difference induced between elements 2 and 1, ω_0 = ultrasonic frequency, and no attenuation is assumed. Notice that if $\theta = 0$, s(t) achieves a maximum value.

The two received signals are input to a synchronous detector, which has, as its output a voltage proportional to θ. This voltage is applied to a phase shifter, which delays the outgoing wave from element 2 to compensate for its subsequent advance through the higher velocity material. The result is an output signal equal to that obtained by an unsegmented transducer, and a homogeneous medium. For the general case of multiple elements and more complex material properties, there would need to be a synchronous detector and phase shifter for each element. As well, any attenuation variations would affect the detector outputs. Consequently, an amplifier/limiter would need to be introduced ahead of the detectors, so that both phase and amplitude are measured and compensated.

A focused beam could be produced by feeding the detectors with reference signals appropriately delayed to form a focus at a desired distance. Returns from the focal region (isolated by means of gates) could then be corrected for material inhomogeneities. Such a system is sketched in Figure 3. Note the fixed delays which determine the desired focus. The variable delays or phase shifters correct for distortions imposed by the medium. If variable delays and timing circuits are used, even pulsed transducers could be focused and corrected.

In the discussion to this point, we would need an echo signal within the time gate in order to get the information required for correction. In case there is none, the phase shifters would simply be nulled. As the transducer is scanned, the array is continually corrected in real time. Thus, there should be little deterioration of response due to material variations. Since the correction is electronic, high speed is possible. In the optics situation, where electro-mechanical actuators are usually required, real-time means slow-time. Fortunately, atmospheric turbulence is also quite slowly varying.

The system shown in Figure 1(b) could be used in other modes on materials that are homogeneous. For example, if a flaw is detected during a routine scan, it would be possible to automatically focus the transducer to concentrate maximum energy on the flaw, and keep it there as the transducer is scanned. In this way, a large aperture over which the flaw produces a large echo could be attained. SAFT methods, for example, could then be used to obtain a sharp image of the flaw. The way this system works is shown in Figure 4 in the simple two-element configuration.

In this system, called aperture tagging or multidither, one element is phase-dithered at the relatively low frequency ω_1. At the crack tip, the waves from the two elements interfere, alternately destructive and constructive. The reflected output will thus be amplitude modulated at the dither frequency ω_1. A low pass filter in the synchronous detector passes all but the slowly varying component, which is proportional to the intensity of the output signal. Hence, the phase of element 2 is driven so as to achieve a maximum output signal. At this point, maximum energy is concentrated on the glint from the most prominent feature of the flaw. As the transducer is scanned, the system tracks the glint, constantly maximizing the energy on the glint. Mathematically, the output signal is:

$$s(t) = \sqrt{2}[1+\cos(\theta+a \sin \omega_1 t)]^{1/2} \exp j\frac{(\theta+a \sin \omega_1 t)}{2} \qquad (2)$$

where ω_1 = dither frequency, and a = dither amplitude.

When this equation is plotted, we find that the amplitude achieves its maximum when phase passes through zero (provided that $a \geq \theta$). An example computation of phase and amplitude for $\theta = \pi/10$, $a = \pi/2$ is shown in Figure 5.

The intensity $|s(t)|^2$ is input to the synchronous detector to yield a value which drives the dither amplitude to zero when intensity reaches its maximum. To see this, expand $|s(t)|^2$ in terms of Bessel functions to yield the result:

$$|s(t)|^2 \cong 2[1 + J_0(a)\cos \theta - J_1(a)\sin \theta \sin \omega_1 t] \qquad (3)$$

The resulting output of the synchronous detector will be proportional to $J_1(a)\sin\theta$. Thus, as the phase shifter drives ω_1 to zero, the dither amplitude decreases to zero, leaving the phase shift at the proper value to achieve maximum intensity on the glint. In the optical case, θ is a function of time, so the control system is continually adjusting the phase shifter to compensate for the variations. It will also track the glint if it is moving.

In the NDE application, the glint does not move, but the transducer does. So for this application, this technique would be advantageous even for homogeneous materials, because a flaw signal would be maximized over a wide aperture. This is equivalent to having a focused transducer that is angulated to keep the focus on the flaw as it is translated past it.

The extension to a multi-element transducer is straightforward, as shown in Figure 6. Each element must have its own phase shifter driven by its own dither feedback circuit. Each element is "tagged" with its own dither frequency, so that it is independently optimized. The mathematics becomes quite complex, but the total system does converge to keep each element phase to place maximum energy on the flaw. O'Meara (1977) has developed the theory fully, and several optical systems based on this technique have been built and tested.

CONCLUSION

This investigation concludes that both phase conjugation and multi-dither techniques for inspecting CCS materials appear promising. The phase conjugation method is ideal for keeping the ultrasonic beam shape invariant over the scan track by real-time correction of the phase front. The multi-dither method would be useful when a flaw (glint) is detected, at which time maximum energy could be focused on it, even if the transducer position is changed and non-homogeneous material is encountered. Thus, both methods should be useful in CSS materials, and in transition regions, such as welds.

RECOMMENDATIONS

This study has concluded that adaptive ultrasonics could revolutionize UT inspection procedures. It is recommended that an experimental demonstration be conducted quickly. In any case, an invention disclosure will be submitted immediately. Proof-of-principle should be relatively easy, since no exotic technology is required. The following steps are suggested:

Task 1: Two-Element Experiment. A simple experiment using two transducers should be designed and implemented for both methods.

Task 2: Use the two element system to test both concepts.

Task 3: Multi-Element Experiment. A complete multi-element system, comprised of a square 9-element array and associated electronics will be built and tested.

Task 4: The multi-element system will be tested on CSS materials in standard inspection modes using the phase conjugate system, and in tracking mode using the multi-dither method.

It is estimated that the cost of this program will be approximately $250K, with the first two tasks estimated at about $50K. It is strongly believed that this is the threshold of a fundamental improvement in UT, and that this investment will be returned many fold.

REFERENCES

1. Buffington, A, et al, "Correction of Atmospheric Distortion with an Image-Sharpening Telescope," JOSA 67, 298-303; 1977.

2. Buffington, A, et al, "First Observatory Results with an Image-Sharpening Telescope," JOSA 67, 304-305; 1977.

3. Hardy, JW, "Active Optics: A new Technology for the Control of Light," IEEE Proc. 66, 651-697; 1978.

4. Hardy, JW, et al, "Real Time Atmospheric Compensation, JOSA 67, 360-369; 1977.

5. Hayes, CL, "Experimental Test of Infrared, Phase Conjugation Adaptive Array," JOSA 67, 269-277; 1977.

6. O'Meara, TR, "The Multi-dither Principle in Adaptive Optics," JOSA 67, 306-315; 1977.

7. Pearson, JE, "Effects of Speckle in Adaptive Optical Systems," JOSA 66, 1261-1267; 1976.

8. Pearson, JE, "Atmospheric Turbulence Compensation Using Coherent Optical Adaptive Techniques," App. Opt 15, 622; 1976.

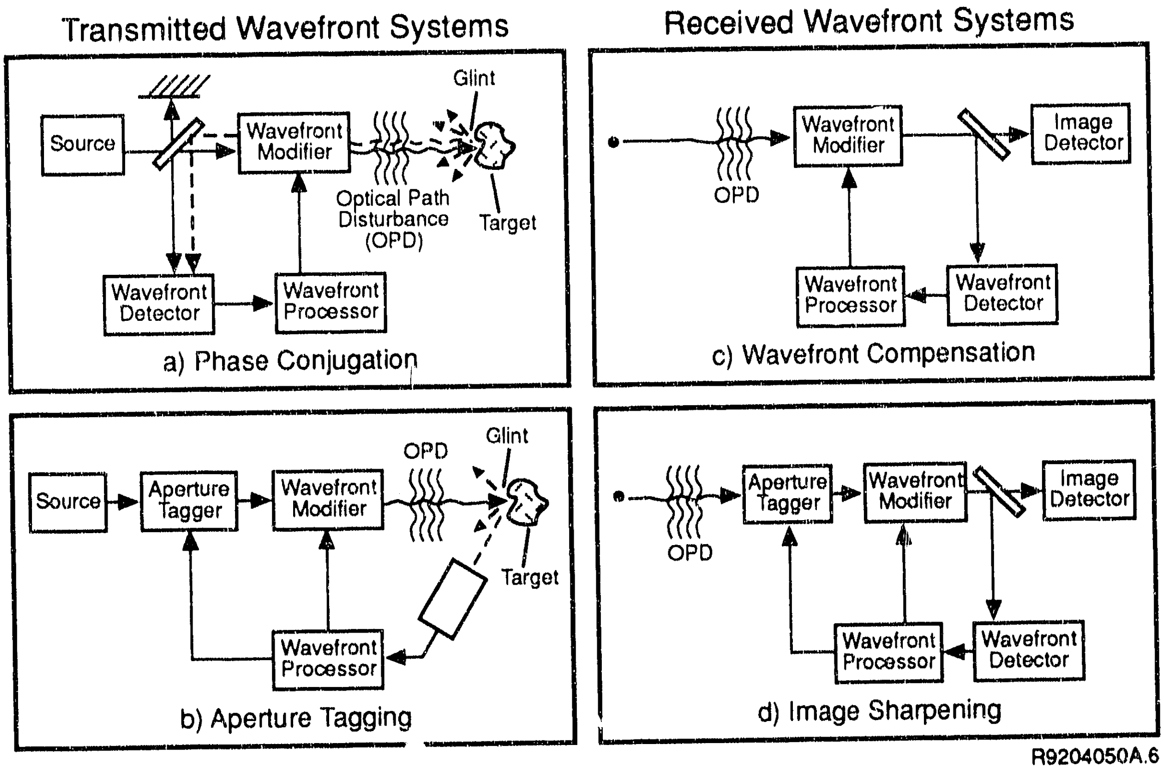

Figure 1. Basic Active Optical Systems after Hardy (1978)

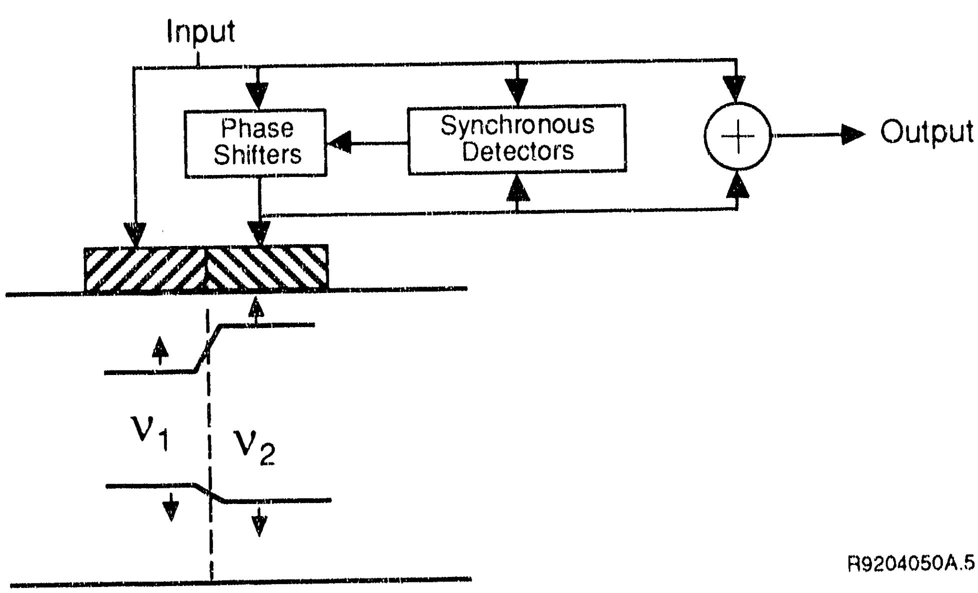

Figure 2. Two-Element Adaptive System

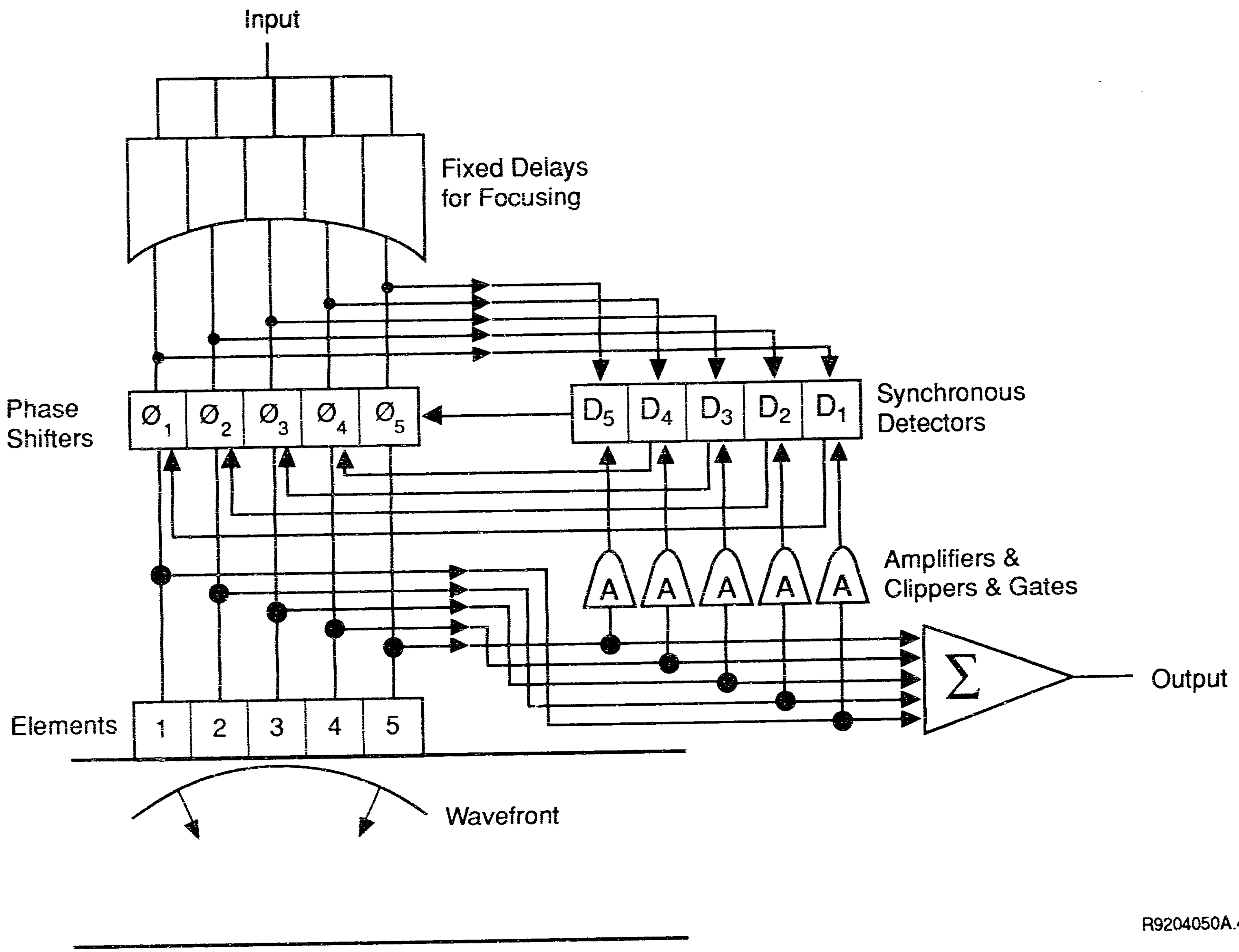

Figure 3. Adaptive Focus Array

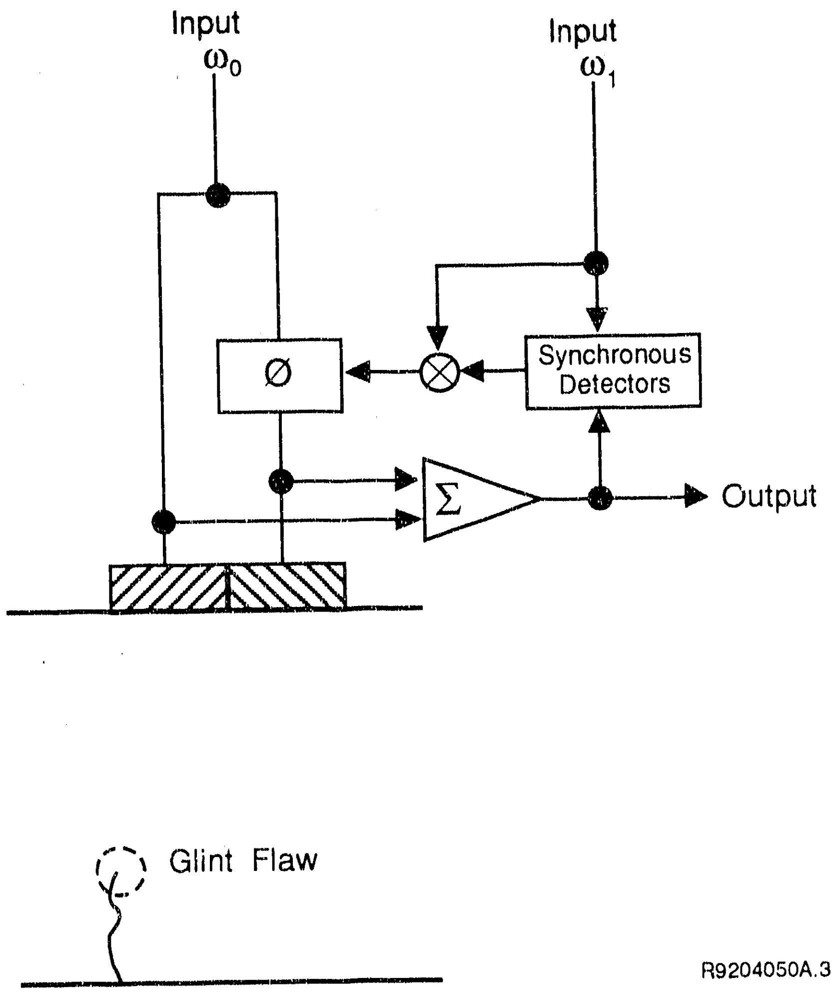

Figure 4. Two-Element Dither System

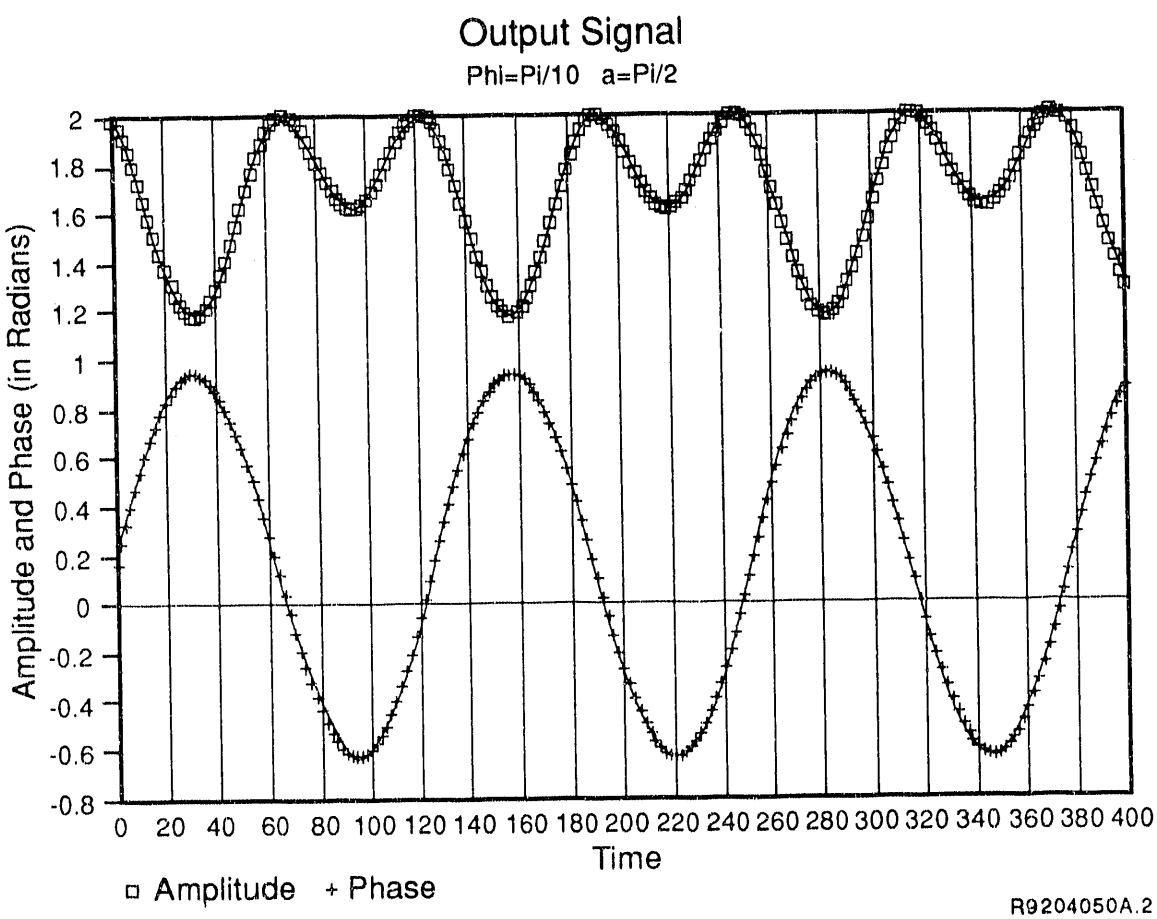

Figure 5. Output of Multi-Dither System

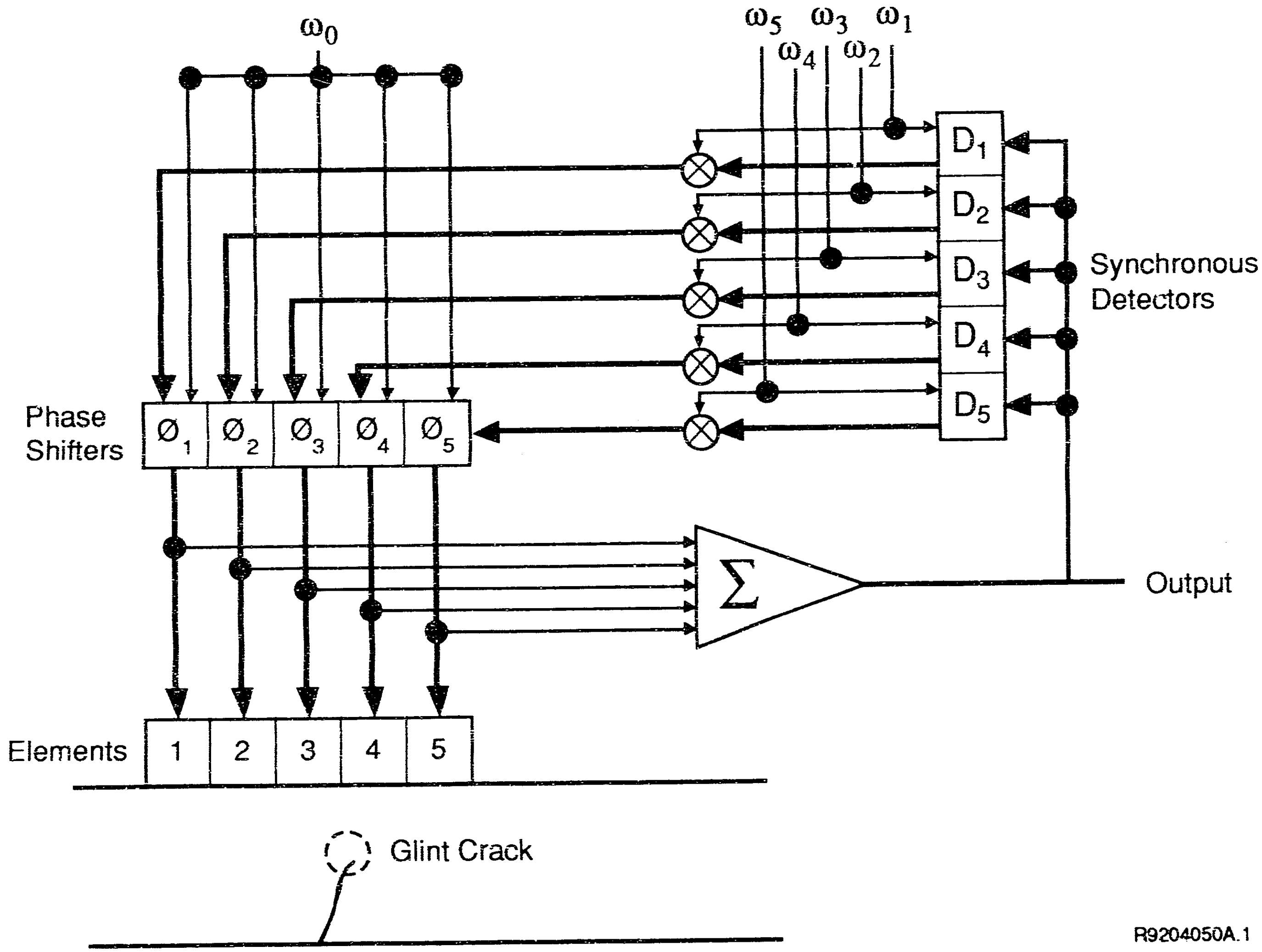

Figure 6. Multi-dither Adaptive System

Appendix B: Phase Mapping of Ultrasonic Fields Passed Through Centrifugally Cast Stainless Steel

by

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PHASE MAPPING OF ULTRASONIC FIELDS PASSED THROUGH CENTRIFUGALLY CAST STAINLESS STEEL

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INTRODUCTION

Mapping of ultrasonic fields passed through various solids has been used as an engineering tool to measure field distortion [1-8]. Centrifugally cast stainless steel (CCSS) has been one material of interest since many pressurized-water reactors (PWRs) use this material in the primary pressure boundary. The two-dimensional mapping of amplitude has been performed in different CCSS microstructures, and it was also of interest to extend this capability to include phase. This data was thought to be useful in validating models which are being refined to predict ultrasonic fields in solids, compensating for phase distortion when imaging reflectors, and detecting flaws by detecting changes caused by interference between the phase response of the primary wave front and a flaw. Previous work indicated that the sound field emitted by a 45°, longitudinal-wave probe was distorted at a frequency of 2 MHz but not at 1 MHz [2]. This report discusses the samples used, the process of mapping the in-phase fringe pattern, and an analysis of the fringe patterns acquired from selected CCSS microstructures at frequencies of 1 and 2 MHz.

CENTRIFUGALLY CAST STAINLESS STEEL

CCSS is characterized as a material containing a coarse microstructure that is anisotropic and heterogeneous. The major microstructural classifications are a columnar, an equiaxed, and a mixed columnar-equiaxed microstructure of which the majority of field material is believed to be the latter. (See Good and Van Fleet for macrographs of each microstructure [2].)

Two CCSS material microstructures were used to acquire ultrasonic field maps: an equiaxed microstructure and a columnar microstructure. In order to acquire reference field maps from a homogeneous-isotropic material, a carbon steel pipe section that had an equivalent diameter and wall thickness was used. All samples were field pipe sections and had a 70-cm inner diameter and a 6-cm wall thickness.

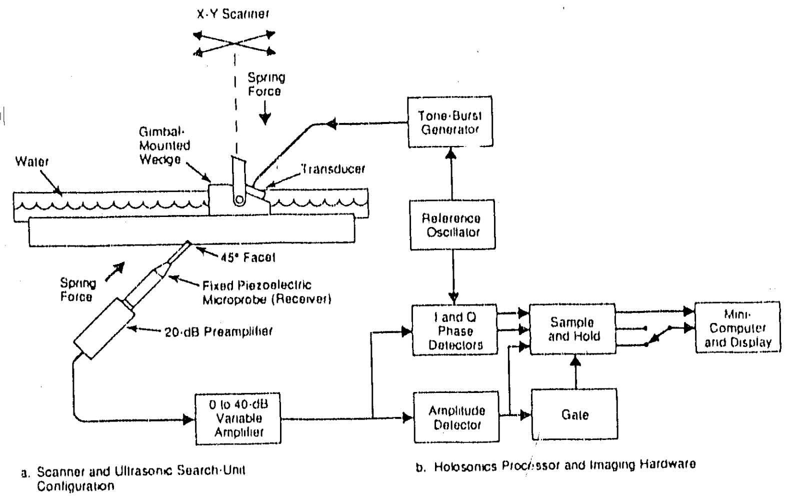

Fig. 1. Data acquisition system for sound field mapping

A spatial coordinate reference had been placed on each sample. This included the pipe axial and circumferential axes as well as points on the two diametrical surfaces which only differed in radial position and/or axial displacement [4]. A small, 45° facet was also present on the inner diametrical surface for placement of the microprobe receiver.

Ultrasonic Field Map System

The ultrasonic field mapping system provided a two-dimensional map of the ultrasonic field (Fig. 1). Longitudinal-wave field maps were obtained using a longitudinal-wave probe as a transmitter and a longitudinal-wave microprobe as a receiver[1]. The width of the lead-zirconate-titanate (PZT) chip within the microprobe was 0.3 mm (0.01 inch). A scan was accomplished by applying the microprobe (Fig. 2) to a 45° facet and scanning in a raster format with the transmitting probe. No special surface preparation was performed for application of the microprobe except for machining the 45° facet. The purpose of the facet was to enhance the receiving directivity pattern [4].

A major system change was use of a real-time gate. Previous data involved digitizing the RF signal and implementing a software gate via post-processing [4]. Interactive positioning of the gate assured that the proper portion of the signal was gated; however, a system upgrade had not been completed which would permit phase measurement and software gating. A modified Holosonics scanner and imaging system was used to permit a preliminary evaluation.

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[1]Piezoelectric apertures are typically many wavelengths across, which generally makes the transducer unable to uniquely distinguish signal phase. A piezoelectric microprobe less than a half-wavelength across, however, is always able to uniquely distinguish phase. This characteristic of the microprobe is denoted as "phase insensitivity" and is not to be confused with the ability of the microprobe to detect phase.

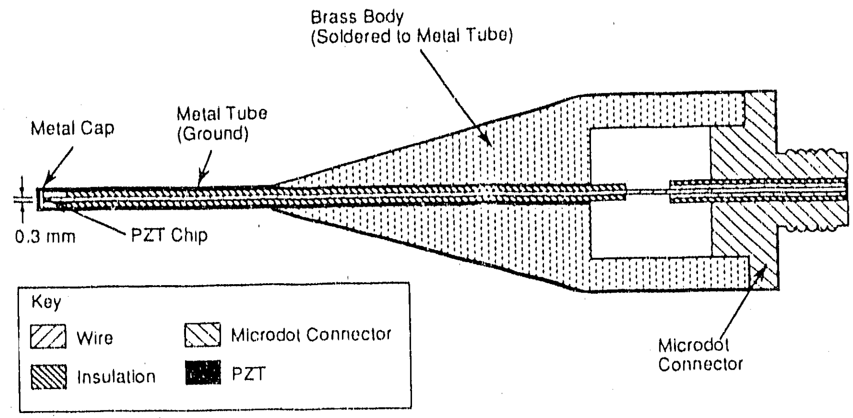

Fig. 2. Design schematic of ultrasonic microprobe (PNL design)

The Holosonics system used a reference oscillator to provide input to the tone-burst generator and in-phase and quadrature-phase detectors. Transducer excitation was accomplished by gating the continuous-wave signal and using a 40 W amplifier. By referencing the in-phase and quadrature-phase detectors to the continuous-wave signal, two time modulated signals were produced where voltage was respectively proportional to $A \cdot \cos\theta$ and $A \cdot \sin\theta$.

Ultrasonic field maps were formed by determining the response in the gate. The gate was used in either a fixed mode where a constant time delay was set or a signal-following mode. While in the signal-following mode, the gate was turned on at the first occurrence of the amplitude detector breaking a threshold. Images were made by two dimensionally mapping the gated value of each respective detector to the coordinate system of the scanner. A preset color or gray-scale level was assigned to the quantum level of the analog-to-digital converter. No amplitude normalization was performed on the images.

An 18 dB dynamic range existed between the gate threshold and saturation of the phase detectors. Amplitude variation while performing a two-dimensional scan, however, was much greater than this range. To minimize gating errors while collecting phase data, system gain was increased beyond the saturation limit of the detectors. This enabled the gate while in the signal-following mode to accurately track the longitudinal wave and still permitted a qualitative comparison of phase since the resulting fringe pattern still displayed the cyclic variation of $A \cdot \cos\theta$ and $A \cdot \sin\theta$.

Since amplifier saturation prevented amplitude reconstruction, another field map was performed with system gain reduced to assure a linear response. The amplitude map provided a spatial reference of the field. Since the signal-following gate did not function well when system gain was reduced, the gate was used in the fixed mode.

<u>Data Acquisition</u>

System parameters were set prior to collecting each field map. When collecting phase data the gate was placed in the signal-following mode. The tone-burst duration and gate delay respectively were set at 9

μs and 5 μs. When collecting amplitude data, the delay was set such that the gate occurred 5 μs into the longitudinal signal when the operator had peaked the response by translating the transmitter with the scanner.

The same acrylic wedge was used as in previously reported work [2-4]. An 18.7° incident angle was used to produce a nominal 45° longitudinal-wave field for all three samples. The scrubbing surface of the wedge had been contoured to match the outer pipe radius.

Due to the large pipe wall thickness, transducer diameters were selected such that the near field zone was extended to approximately 6 cm, which is the pipe wall thickness. A 3.8 cm (1.5 inch) diameter transducer was mounted on the wedge for acquiring 1 MHz data and a 2.5 cm (1.0 inch) diameter transducer for acquiring 2 MHz data. The path length in the wedge was 23 mm (0.89 inch).

Prior to making a scan, the scanner was aligned to the sample. This involved translating the wedge with the scanner and visually inspecting the offset between the wedge and scribe lines on each sample. The scribe lines on the outer diametrical surface were the pipe axis, circumference, and spatial reference point relative to the facet on which the microprobe was placed [4].

<u>Data Analysis</u>

Data analysis was performed on images acquired from each of the samples at 1 MHz and 2 MHz (Figs. 3 and 4). The reference scans served an important function in that the ultrasonic field propagated through a geometrically similar condition to that of the coarse-microstructural material being evaluated. If an insignificant amount of distortion had occurred due to the CCSS, the refractive, diffractive, and phase phenomena should be similar to the reference scans and contain similar image features. The degree of distortion incurred, therefore, was determined by comparing the ultrasonic field map to the reference scan. Although this was a subjective process, basic conclusions concerning distortion and trends were established.

Prior to analyzing the data, clarification may be needed to define the fringe pattern of the acquired phase maps. The imaged plane was at 45° relative to the propagational direction of the ultrasonic field (Fig. 1). Therefore, the individual ray paths were a function of distance and angle. The angular dependence was important since wave velocity was dependent on the angle between the grain axis and the propagational direction of the wave [5].

The recorded images mapped the output of the in-phase detector; i.e., $A \cdot \cos\theta$. At (X,Y) equal to (7.6 cm, 0 cm) the wave front passed through the least amount of material. This position also corresponded to a refracted angle of 0°. As Y increased, the angle and through-propagated distance increased according to the respective relations:

$\theta = \arctan(Y/T)$ where T was the sample thickness and

$S = T/\cos\theta$.

A fringe then occurred for each successive wavelength; i.e. a 360° change of θ. An obvious perturbation of the fringes were the 180° phase shifts (one half of a fringe) between successive lobes of the wave front. Similar changes also occurred as a function of X. Fringes

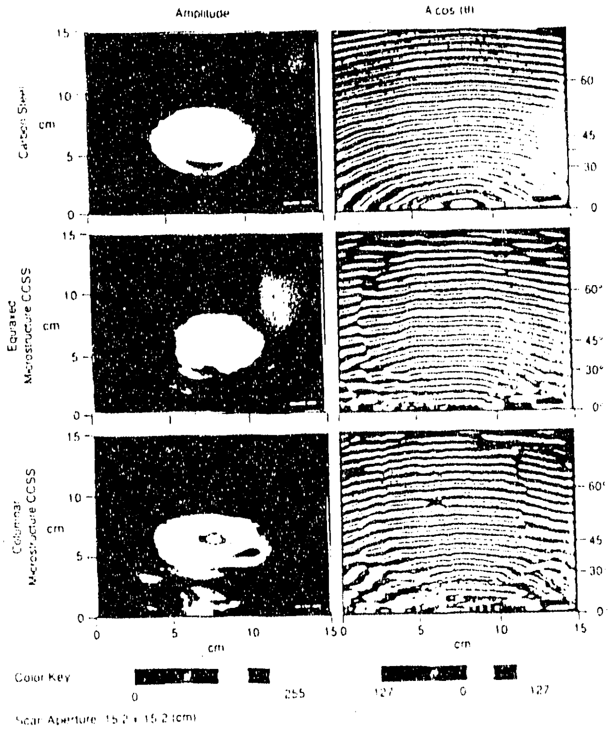

Fig. 3. Ultrasonic maps of 1-MHz, 45°, longitudinal-wave fields

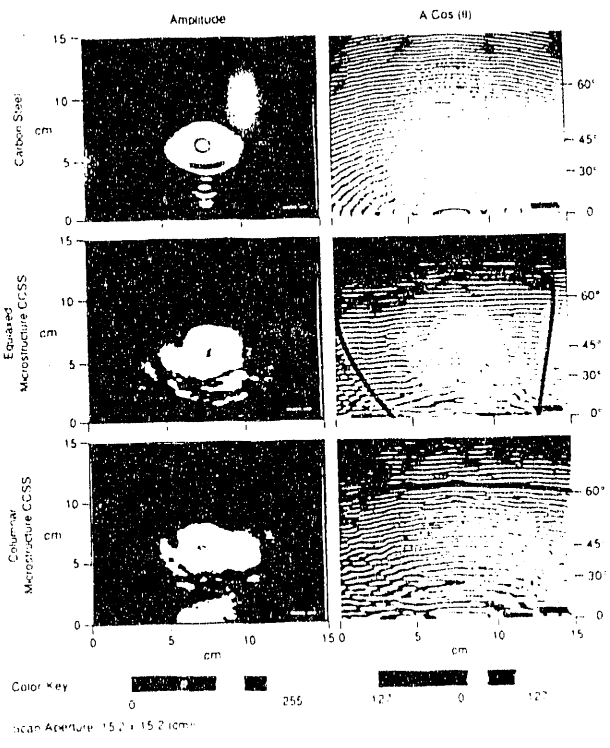

Fig. 4. Ultrasonic maps of 2-MHz, 45°, longitudinal-wave fields

occurred, therefore, due to differences in distance from the 45° plane cutting across the ultrasonic beam, the angular dependence of velocity, and phase shifts between successive lobes of the wave front.

Data indicated that with a 6-mm wavelength (1.0-MHz frequency) the wave was not severely distorted by either the equiaxed or columnar microstructure (Fig. 3). An observation from the carbon-steel data was that the fringes were well behaved as expected and contiguous across the phase shifts between successive lobes. For the equiaxed microstructure, the fringe pattern was relatively flat over the primary lobe. Between the central region and successive annuli, 180° phase shifts were more readily observed than for the carbon-steel reference. For the columnar microstructure, additional disruptions were observed; however, the pattern was not as well defined. A conclusion was that the distortion of the fringe pattern was less than expected.

The lobe pattern was calculated for the experimental setup used to acquire 1-MHz data. This involved use of the relationships

$A(\gamma) = 2\, J_1(x) / x$ and $x = \pi\, (D/\lambda) \sin \gamma$ [9].

where λ was 5.8 mm/μs (0.23 inch/μs).[2] The boundaries between the first four successive lobes were γ = 10.8°, 20.0°, 29.8°, and 40.6°. The acrylic path length of 23 mm (0.89 inch) was transformed into an equivalent steel path of 11 mm (0.42 inch). The resultant pattern (Fig. 5) was similar to that from the equiaxed structure in Figure 3. Differences between the modeled and experimental results may be due to

[2]These relationships are generally accepted for axial displacements greater than three near fields (3N).

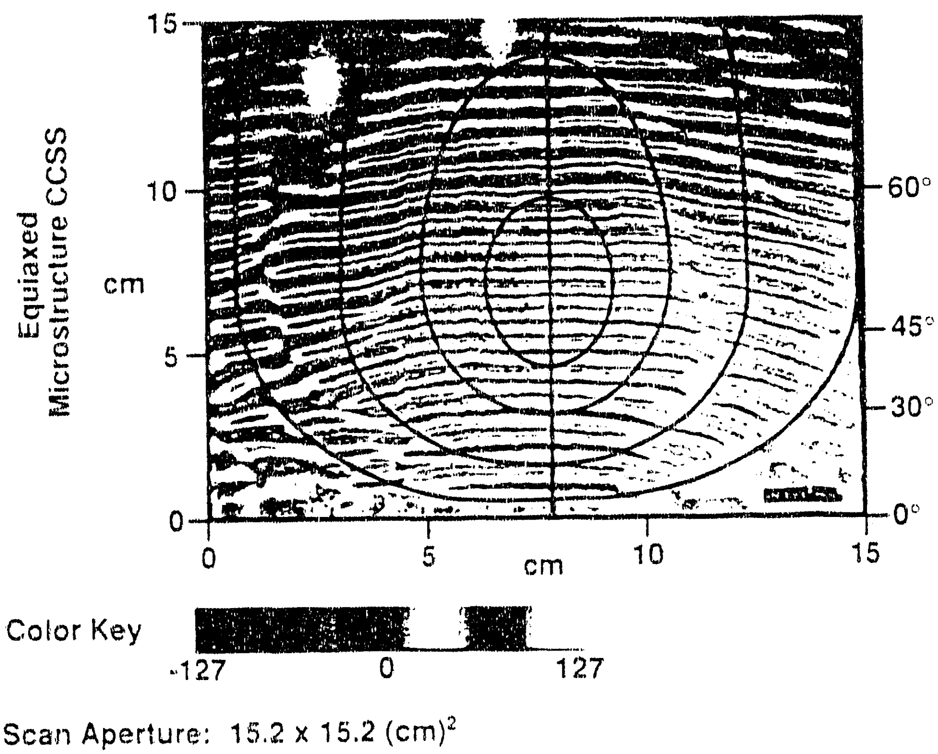

Fig. 5. Predicted lobe pattern of a 1-MHz, 45°, longitudinal-wave field

the region being well within the 3N zone and not accounting for either lensing by the pipe curvature or attenuation by the acrylic wedge. Given these facts, the results were thought to be quite good.

The 3-mm wavelength (2.0-MHz frequency) data indicated that the wave was not severely distorted by either microstructure. Due to the increased attenuation associated with the higher frequency, the surface-following gate did not function properly. For the equiaxed and columnar data, a line was drawn to separate regions where the gate functioned properly and areas where some mistriggering occurred. The entire region containing the principal lobe and most of the remaining area, however, was valid for each microstructure. The amount of disruptions in the fringe pattern was markedly less than anticipated. This gave further support to the position that practical methods may be potentially developed for inspecting CCSS.

The stability of the fringe pattern might be used to detect planar-like flaws. Disruptions in the fringe pattern may result from interference with a flaw response or increased propagational distances due to the partial blockage of a signal. Data might be taken via the external surface of a component by means of a full V-path.

CONCLUSIONS

Ultrasonic field maps were useful in evaluating distortion incurred by waves propagating in materials of coarse microstructure. A piezoelectric microprobe with a 0.3 mm (0.01 inch) active area was used to acquire data. The microprobe aperture was small relative to the wavelength and, therefore, functioned well as a phase-insensitive receiver. Phase maps of 45°, longitudinal-wave fields at 1 and 2 MHz displayed significantly less distortion than was expected.

Use of the fringe pattern might lead to enhanced imaging of reflectors by compensating for phase distortion; e.g., acoustic holography and synthetic-aperture focusing. The stability of the fringe pattern was also thought to be a potential technique for detecting planar-like reflectors such as cracks. Detecting flaws would require data acquisition from an exposed surface. One might use a full V-path by applying the transmitter and microprobe receiver on the outer surface. Fringe-pattern disruptions may result from partial blockage of the wave front by a planar flaw and interference between the two signals.

System improvements would include digitization of the in-phase and quadrature-phase signals and implementation of a software controllable gate. Currently, the system relies on a hardware gate that operates in either a fixed or signal-following mode. While operating in the signal-following mode, the gain levels required to trigger the gate are near the saturation limit of the amplifiers. A software gate would permit data acquisition in the linear range of the signal amplifiers and signal-following of either longitudinal or shear waves. This would then permit implementation of an unraveling algorithm for measuring phase.

Future work would include data acquisition of longitudinal and shear waves, expansion of the sample set to include mixed microstructural modes, an evaluation of phase compensation to enhance imaging of large crack-like reflectors, and phase unraveling.

ACKNOWLEDGEMENTS

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REFERENCES

1. Becker, F. L. and L. J. Busse in 1982 Paper Summaries ASNT National Conferences (American Society for Nondestructive Testing, Columbus, Ohio, 1982) pp. 2-8.
2. Good, M. S. and L. G. Van Fleet, in 8th International Conference on NDE in the Nuclear Industry, edited by D. Stahl (American Society for Metals International, Metals Park, Ohio, 1987) pp. 657-666.
3. Good, M. S. and L. G. Van Fleet, in Review of Progress in Quantitative Nondestructive Evaluation, edited by D. O. Thompson and D. E. Chimenti (Plenum Press, New York, 1988), Vol. 7A, pp. 637-646.
4. Good, M. S. and E. R. Green, in Review of Progress in Quantitative Nondestructive Evaluation, edited by D. O. Thompson and D. E. Chimenti (Plenum Press, New York, 1989), Vol. 8A, pp. 889-896.
5. Kupperman, D. S., K. J. Reimann, and D. I. Kim, in Nondestructive Evaluation: Microstructural Characterization and Reliability Strategies, edited by O. Buck and S. M. Wolf (The Metallurgical Society of American Institute of Mining Metallurgical, and Petroleum Engineers, Warrendale, Pennsylvania, 1981), pp. 199-216.
6. Kupperman, D. S., K. J. Reimann, and D. Yukas, in Quantitative NDE in the Nuclear Industry, Proceedings of the Fifth International Conference on Nondestructive Evaluation in the Nuclear Industrys (American Society for Metals, Metals Park, Ohio, 1983) pp. 172-175.
7. Rawsthorn, L. R., R. A. Murgatroyd, and T. Bann, The Effects of Austenitic Stainless Steel Double-Layer Strip Cladding on the Propagation of Ultrasound Parallel to the Cladding Strips, United Kingdom Atomic Energy Authority Northern Division Report ND-R-889(R), 1984. Risley Nuclear Power Development Establishment, Risley, Warrington.
8. Yoneyama, H., S. Shibata, and M. Kishigami, in NDT International, Vol. 11, 1978, pp. 3-8.
9. Krautkramer, J., and H. Krautkramer, Ultrasonic Testing of Materials, Third Edition (Springer-Verlag, New York, New York, 1983), pp. 66-67.

Appendix C: UT Measurements Performed on CCSS Material Contained within PISC III Action 3 NDW Assembly 25

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UT MEASUREMENTS PERFORMED ON CCSS MATERIAL CONTAINED WITHIN PISC III ACTION 3 NDW ASSEMBLY 25[a]

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INTRODUCTION

PISC III Action 3 NDW Assembly 25 contained centrifugally cast stainless steel (CCSS) which was ultrasonically characterized by the Pacific Northwest Laboratory (PNL). Personnel from PNL traveled to the site of the PISC block, Southwest Research Institute (SwRI) in San Antonio, Texas, U.S.A. in order to expedite shipment of the block to France. Prior to the trip, various CCSS characterization techniques were attempted at PNL to determine guidelines for characterizing the CCSS material contained within the PISC block, Figure 1. The initial three techniques examined at PNL were those used by D. S. Kupperman et al [1], i.e. ultrasonic-field skewing, V_L/V_S ratio, and V_L. Additional techniques were attempted at PNL and during material characterization. These included T_S/T_L ratio (a modification of V_L/V_S ratio); SV-wave V-path; and L-wave, normal-beam attenuation.

This report documents the technique evaluation at PNL, characterization of CCSS material in the PISC assembly, and conclusions.

[a] Work supported by the U.S. Nuclear Regulatory Commission under Contract DE-AC06-76RLO 1830; FIN B2289; Dr. J. Muscara, NRC Program Manager.

TECHNIQUE EVALUATION AT PNL

Ultrasonic-field skewing was attempted in the laboratory at PNL prior to the trip to SwRI. The technique was described as a pitch-catch arrangement where two 45°, SV-wave search units were used (Figure 2). DS Kupperman et al reported using a 0.5 MHz, 2.5 cm diameter transmitter and observing a strong principle field and angled side lobe [1]. The receiver was positioned to optimize reception of the primary 45° SV-wave field reflected from the inner diametrical surface and the mode converted L-wave field from the SV-wave side lobe. For columnar material, the difference between the separations for maximum SV-SV and SV-L signals was reported smaller than for equiaxed material.

Ultrasonic-field skewing data obtained at PNL indicated that the mode converted L-wave field was difficult to detect and that the principle SV-wave field was detectable. Observations by PNL were that the 45° SV-wave field was detected when examining a fine, equiaxed microstructure and search-unit separation corresponded to a near 45°, full "V" path. Detection of the 45° SV-wave field, however, was inconsistent when examining columnar material. When the field was detected, search unit separation was much less and inferred an angle much less than 45°. Therefore, the presence of a strong 45° SV-wave field at a true 45° path was determined by PNL to be a feature of equiaxed material while inconsistent reception with an angle much less than 45° was a feature of columnar material. This discriminant technique of using two transducers via pitch-catch was defined by PNL as "SV-wave V-Path."

The ratio of L- and S-wave velocities was acquired by D. S. Kupperman et al [1]. PNL obtained the measurement by bonding a 2.5-cm diameter, 1-MHz, normal-beam, shear-wave transducer to the CCSS. Bonding via epoxy was required to obtain an adequate signal-to-noise ratio (SNR). A 30 dB signal level improvement resulted when changing from shear-honey coupling to a fast curing (5 minute) epoxy, however, the SNR still remained poor due to coherent noise presumably from the microstructure.

A requirement set by PNL for selecting the correct signal was establishing the time reference, $t_{0,}$ via calibration; measuring the arrival time of the first backwall signal, and estimating the arrival time of the second backwall signal by doubling the time. The pulse overlap technique was then employed between the first and second backwall signals to determine the S-wave time-of-flight (TOF), Figure 3. This technique was also used for L-wave TOF measurements which were easily performed due to the good SNR of the received L-wave fields. The overall bi-polar signal and expanded view of the overlapped backwall responses were recorded in one photograph, Figure 3A for the S-wave in equiaxed material and 3B for the S-wave in columnar material.

The V_L/V_S ratio is mathematically equivalent to T_S/T_L ratio. Since true pipe thickness is not generally known in the field, the T_S/T_L ratio is a more appropriate term since field measurements are time measurements instead of velocity measurements. Henceforth in the report, the procedure is referred to as the "T_S/T_L" technique. Another comment is that while L-wave pulse overlap was usually unambiguous, the S-wave pulse overlap measurement was subjective and to some degree, art work.

L-wave velocity was also suggested as a discriminant where equiaxed material had a lower velocity but a greater variation than did columnar material [1]. V_L was respectively measured to be 5.8 mm/μs and 5.5 mm/μs for pure equiaxed and columnar materials or a 7 percent difference (Figure 4). The variance was much less than this for either a pure columnar of fine grained equiaxed material and provided an excellent discriminant. However, for coarse equiaxed and mixed materials the variance was as large as the difference. PNL hypothesized that the velocity variation for equiaxed materials was proportional to grain size.

PNL measurements of pure equiaxed and columnar materials confirmed the reported values. Variance was evaluated by moving the probe manually over the material while viewing the backwall signal on a CRT. PNL observations were that 1) the TOF measurement for calculating V_L measurement was easily made except occasionally in the mixed mode materials and 2) the variance of V_L was small within either the pure columnar or equiaxed material but not in the mixed microstructures. This discriminant technique was defined by PNL as "V_L."

CHARACTERIZATION OF CCSS MATERIAL IN THE PISC ASSEMBLY

The PISC block appeared to have a very good surface finish which occasionally had some scratched and bumped areas that seemed very minor. PNL personnel accomplished the following measurements T_S/T_L; V_L; SV-wave V-path; and L-wave, normal-beam attenuation. A description of new techniques, modifications to previous techniques, the data collected, and an analysis is presented.

The instrumental setup for data acquisition used an adjustable band-pass filter to aid the comparison of calibration data to data acquired from the PISC assembly (Figure 5). A better comparison was permitted with the filter due to the large discrepancy in attenuation between that of the CCSS material and the wrought-stainless-steel calibration piece. The procedure was to manually scan the CCSS material and estimate the frequency response of the signals of interest. The filter was then adjusted to restrict higher frequency components that would have been apparent in calibration data but not in the CCSS data. Otherwise, excessive attenuation would have been attributed to the CCSS at a specified frequency due to the material acting as a low-pass filter.

T_S/T_L Data

Normal incidence S- and L-wave transducers were used to determine the T_S/T_L ratio. The procedure was altered from that defined earlier since increased difficulty existed when detecting the S-wave. The L-wave measurement was performed first since it had a good SNR and also provide a guideline for predicting an appropriate temporal value for measuring the S-wave TOF. The temporal range was calculated on the basis that for equiaxed material the T_S/T_L ratio is 1.88 while for columnar material the ratio is 1.55. Data was acquired from selected locations (Figure 6) and recorded with the pipe coordinates (X, Y) as defined in Figure 1. The data was then transferred onto a map of the PISC block (Figure 7). (CCSS material, ASTM A 351 CF 8M per Figure 1, spanned from X equal 0 mm to X equal 496 mm.)

The S-wave TOF measurement was very difficult. By comparing the data in Figure 3A and 3B, less interference appeared to be present for equiaxed material than for columnar material. The accuracy of the T_S/T_L ratio was considered low due to the problem of accurately measuring T_S. A conclusion was that the interference observed in the S-wave data from the PISC assembly was more like that of the columnar data collected at PNL than the equiaxed data collected at PNL. By the T_S/T_L-ratio technique the material appeared to range from a pure equiaxed microstructure to a pure columnar microstructure with the majority of material being of a mixed mode.

V_L Data

V_L was measured by using calipers to measure wall thickness and the T_L value used in the T_S/T_L measurement. Wall thickness was measured at the extreme end of the cylinder (X equal to 0 mm) and was assumed to not vary as a function of X. The data was then transferred onto another map of the PISC block (Figure 8).

V_L data was thought to be reliable and repeatable. The measurements were all less than 2.5 percent from the reported value for columnar material. A conclusion was made, therefore, that a high probability exists that the material is a pure columnar microstructure.

SV-Wave V-Path

Two SV-wave transducers were applied in a pitch-catch, V-path configuration. The transducers were manually positioned and shifted across the pipe. A 6.9-cm separation between exit points geometrically inferred a 45° V-path. The 6.9 cm was equivalent to a 2.5-cm separation between the probe wedges. To receive a strong signal the wedges almost needed to be in contact with each other. To prevent cross talk across the wedges, a cardboard sheet was placed between the wedges. Data was acquired at each Y-axis value where T_S/T_L measurements were taken. Scanning was done with moving the transmitter-receiver pair slowly along the X-axis while repeatedly sliding one transducer so that the distance between wedges varied between 5 cm and 0 cm. In this way approximately 11 paths were scanned, e.g. Y equal to 0°, 30°, 60°, 100°, 130°, 160°, 190°, 220°, 250°, 290°, and 320°. Each path spanned X from 25 to 475 mm due to restrictions from the wedges and span of the CCSS material.

During data acquisition signals were unstable and the peaked response occurred for angles much shallower than 45°. In general the peaked response occurred for a separation of 1.3 cm to 0.0 cm. There were only a few locations where a hint of a 45° V-path existed. The conclusion was made that the microstructure was either a very coarse equiaxed, mixed mode, or columnar.

L-Wave, Normal-Beam Attenuation

A normal beam L-wave transducer was applied to the surface and the amplitude of the first backwall surface monitored. The amplitude values for 13 unique points and calibration were acquired. Recorded values were as follows:

TABLE 1. Recorded L-wave, Normal Beam Amplitude Values

No.	Coordinate Position (X,Y)	Peak-to-Peak Voltage
Cal.	---	1,115 mV
1	(150 mm, 0°)	626 mV
2	(380 mm, 0°)	602 mV
3	(150 mm, 30°)	666 mV
4	(380 mm, 30°)	600 mV
5	(270 mm, 65°)	634 mV
6	(150 mm, 95°)	680 mV
7	(380 mm, 130°)	580 mV
8	(150 mm, 160°)	785 mV
9	(380 mm, 195°)	570 mV
10	(150 mm, 225°)	610 mV
11	(380 mm, 260°)	600 mV
12	(150 mm, 290°)	555 mV
13	(380 mm, 320°)	565 mV
		621 mV Mean
		59 mV Standard Deviation

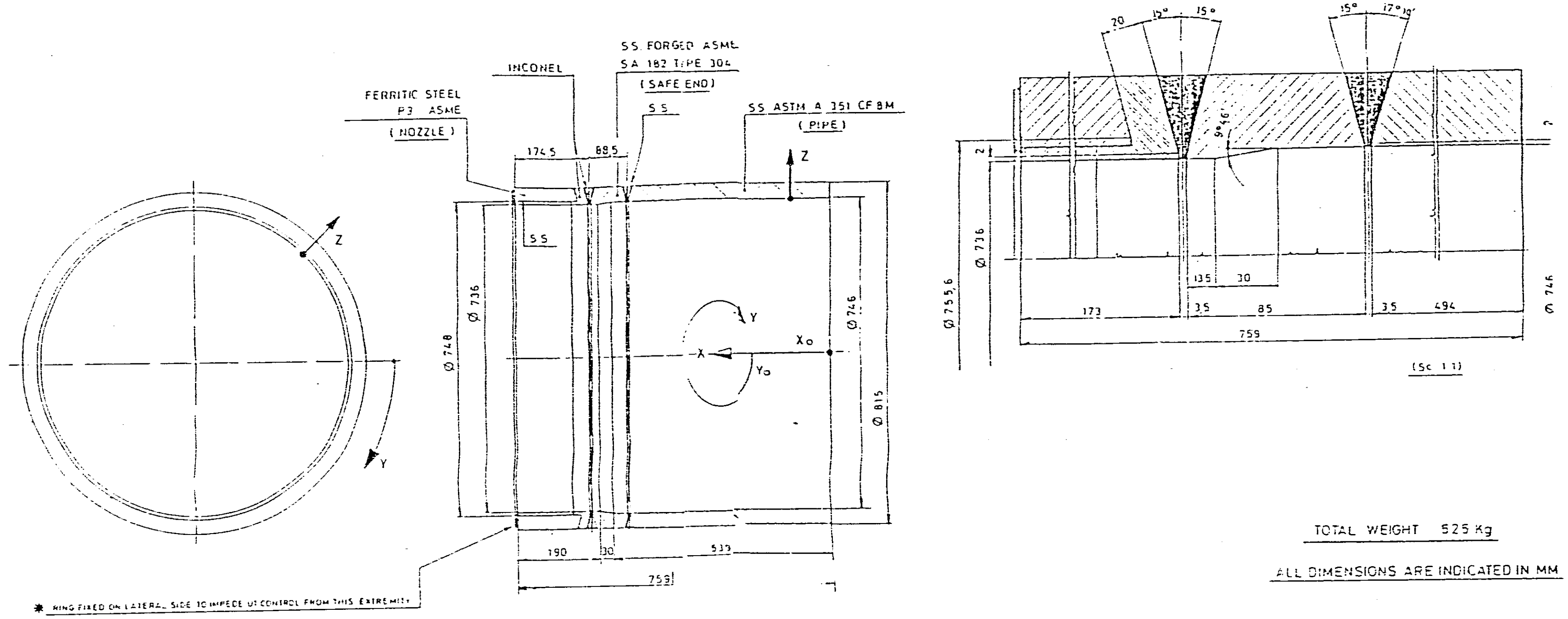
The mean value was -5 dB relative to the calibration data or -1.5 dB per cm of material. The calibration material was a 3.3-cm thick, wrought, 304-stainless-steel pipe section with an as-manufactured surface condition. The thickness of the CCSS material by Figure 1 was 34.5 mm. Similar measurements performed at PNL resulted in -0.8, -1.3, and -1.2 dB per cm for equiaxed-, columnar-, and mixed-microstructural pipe sections of thickness 5.8 cm and calibrated to carbon steel. Due to the similarities in attenuation, this test was not considered sensitive as a discriminant for microstructural characterization.

CONCLUSION

Multiple techniques were implemented to characterize the CCSS material in PISC NDW Assembly 25. Most of these techniques were unable to aid in the classifying the microstructure. The V_L technique was the only technique which resulted in what was thought a reliable and repeatable measurement. The measurements were all less than 2.5 percent from the reported value for columnar material. A conclusion was made, therefore, that a high probability exists that the material is a pure columnar microstructure.

REFERENCE

1. Kupperman, D. S., K. J. Reimann, and J. Abrego-Lopez. 1987. "Ultrasonic NDE of Cast Stainless Steel" in NDT International, Vol. 20, No. 3, pp 145-152.



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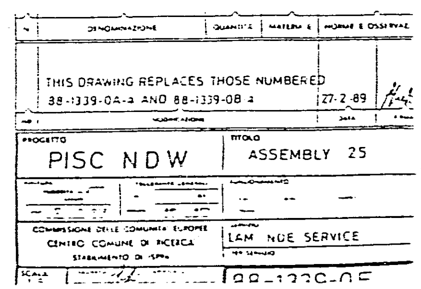

FIGURE 1. Drawing of PISC NDW Assembly 25

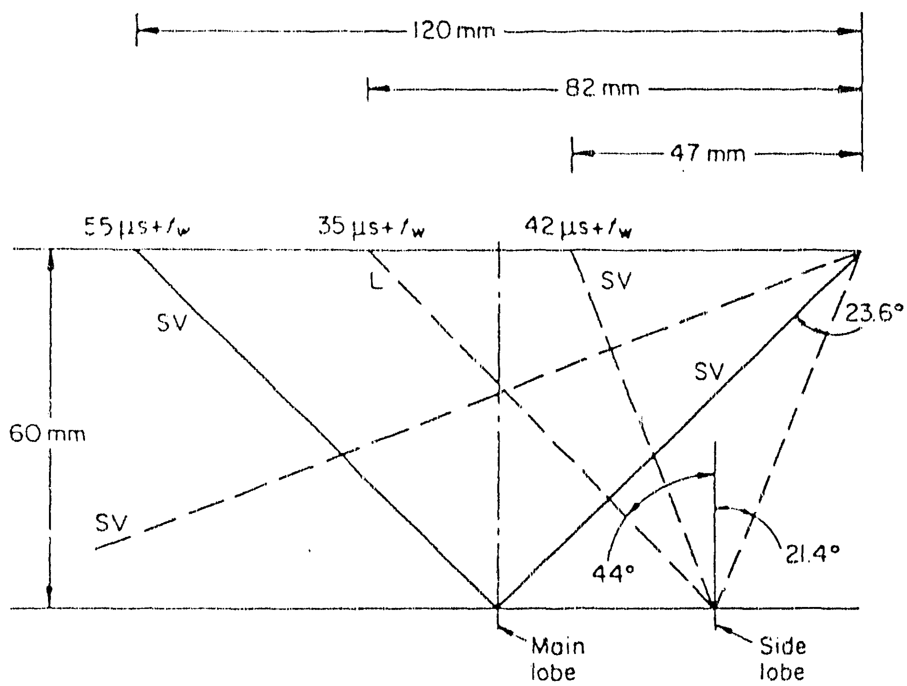

Fig. 3 Schematic showing the main and side lobes of a 25.4 mm, 0.5 MHz 45° SV-wave probe and resulting mode-converted beams after reflection off the sample bottom

<u>FIGURE 2</u>. The Ultrasonic-Field Skewing Technique

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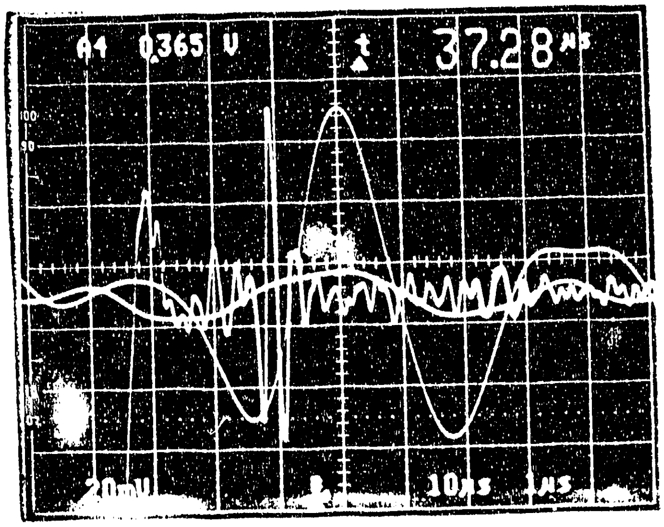


Wall Thickness = 58.12 mm

TOF (S-wave) = 37.28 μS

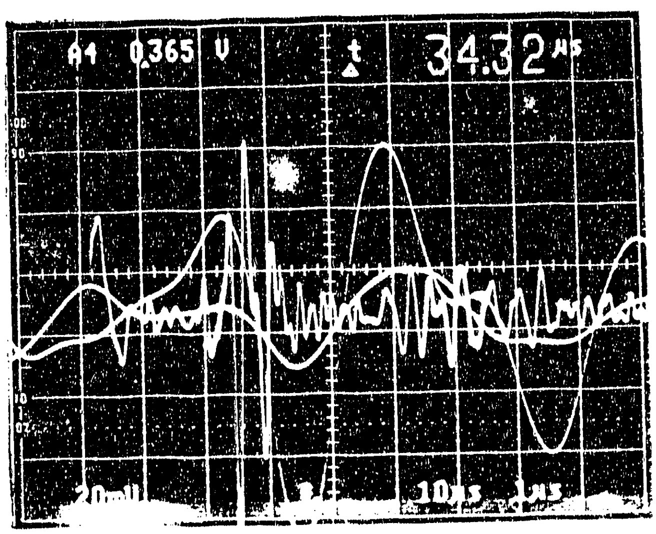
TOF (L-wave) = 19.90 μS

V_S = 3.12 mm/μs

V_L = 5.84 mm/μs

V_L/V_S = 1.88

A) S-Wave Time-of-Flight from Equiaxed Material



Wall Thickness = 60.63 mm

TOF (S-wave) = 34.32 μS

TOF (L-wave) = 22.20 μS

V_S = 3.53 mm/μs

V_L = 5.46 mm/μs

V_L/V_S = 1.55

B) S-Wave Time-of-Flight from Columnar Material

FIGURE 3. Velocity Data Obtained via Pulse-Overlap Technique - (Photographs display pulse-echo overlay data used to determine S-wave TOF)

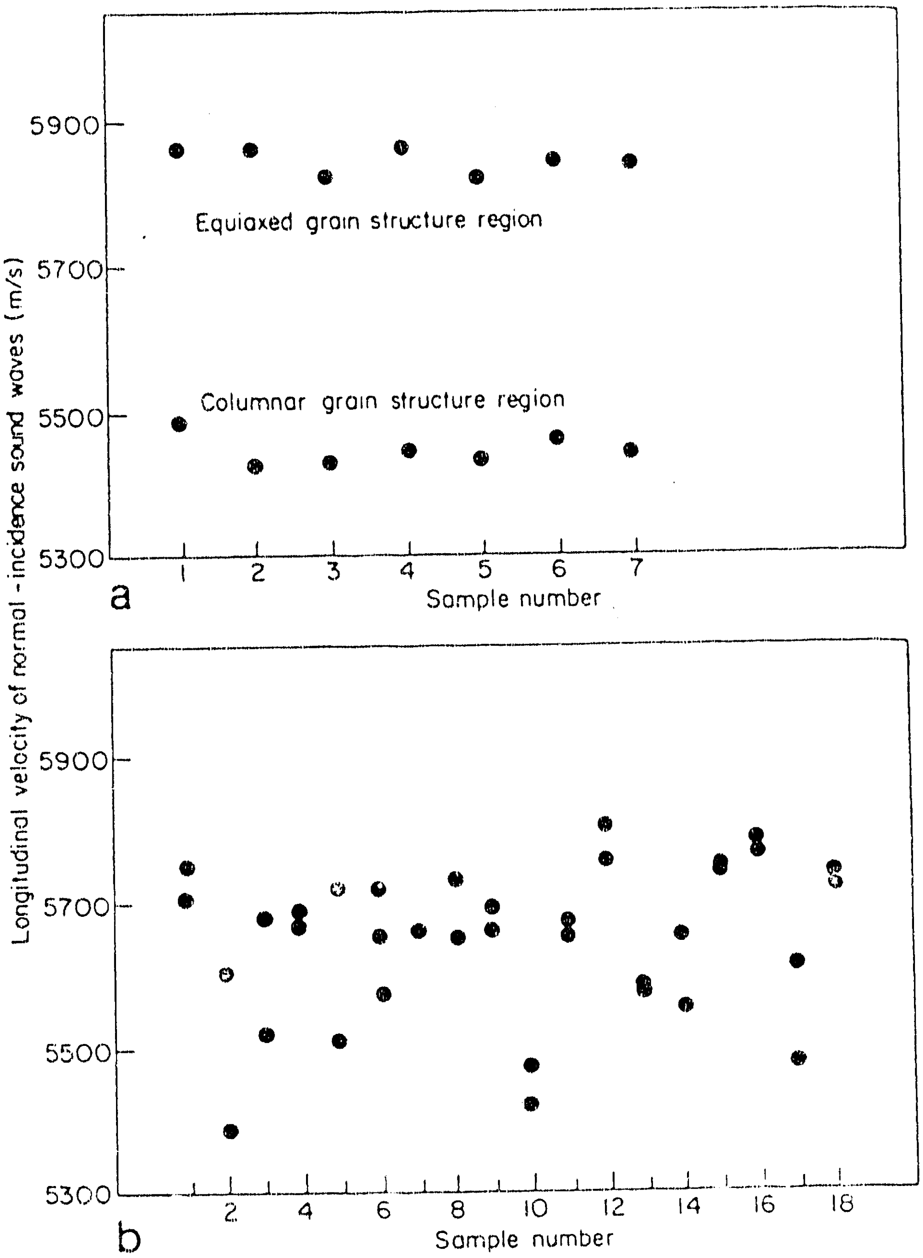


Fig. 1 Variation of longitudinal sound velocity in large-diameter CSS pipe sections: (a) samples with both columnar and equiaxed regions (Battelle samples); (b) samples with a poorly defined, coarse grain structure (Westinghouse samples). Two measurements were made on each sample.

<u>FIGURE 4</u>. Longitudinal Wave Velocity

a) Equiaxed Microstructure b) Columnar Microstructure

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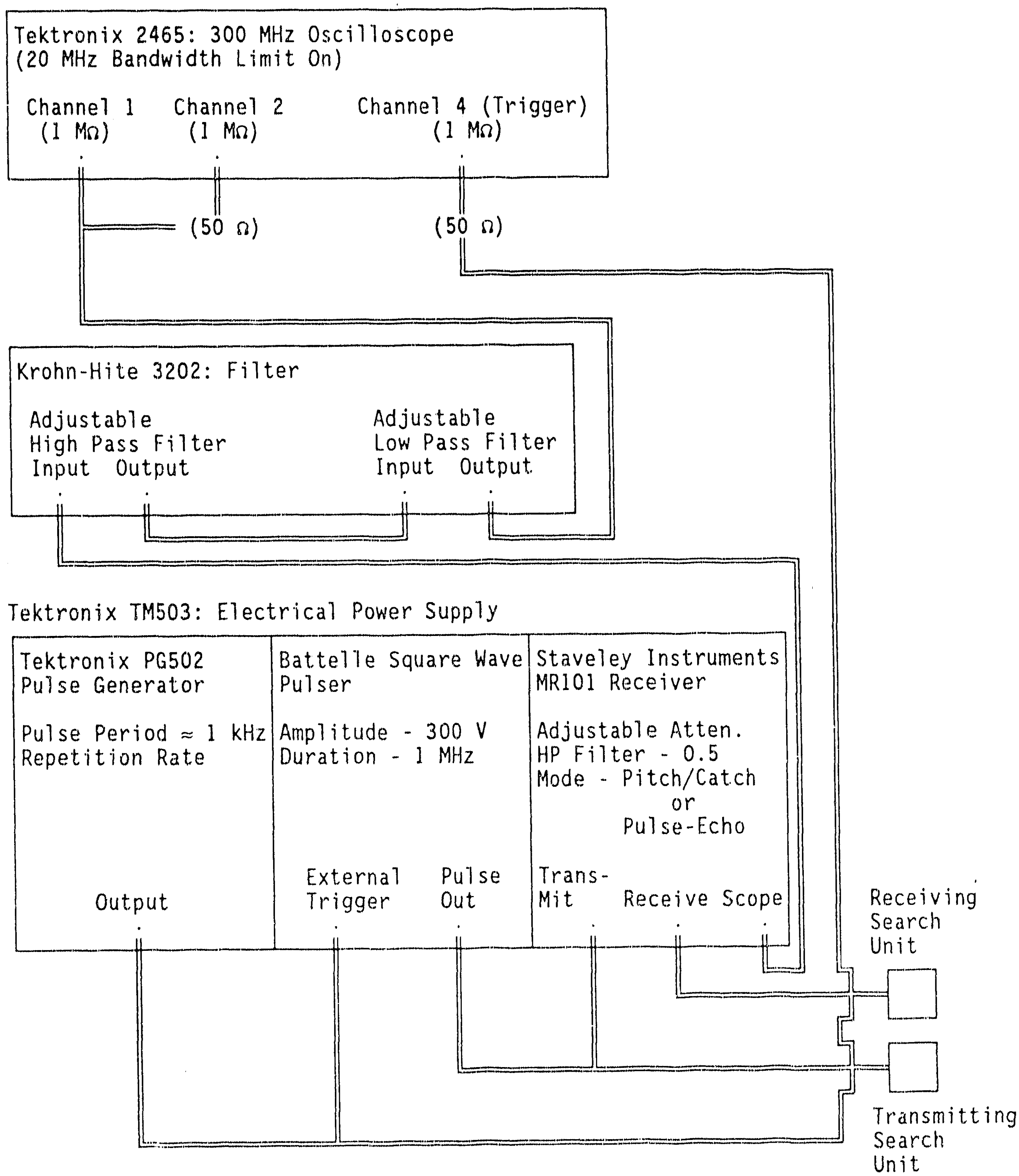
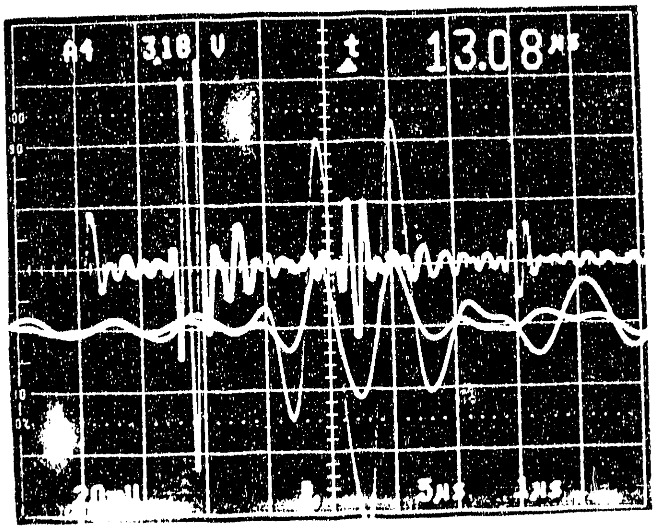


FIGURE 5. Schematic of Electronic Instrumentation



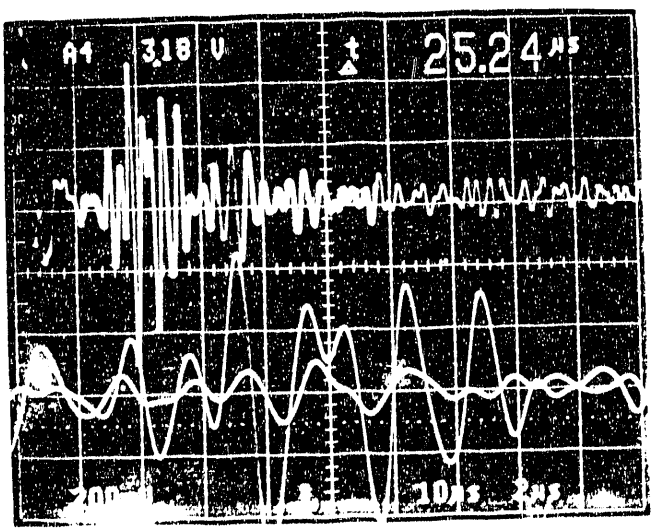
500 kHz < BPF < 2 MHz

Wall Thickness = 34.90 mm

TOF = 13.08 μS

V_L = 5.33 mm/μs

A) L-wave Time-of-Flight



200 kHz < BPF < 500 kHz

TOF = 25.24 μS

T_S/T_L = 1.93

B) S wave Time of Flight

FIGURE 6. L-Wave TOF, Wall Thickness, V_L, S-Wave TOF, and T_S/T_L Measurements at (X) (127 mm, 290°)

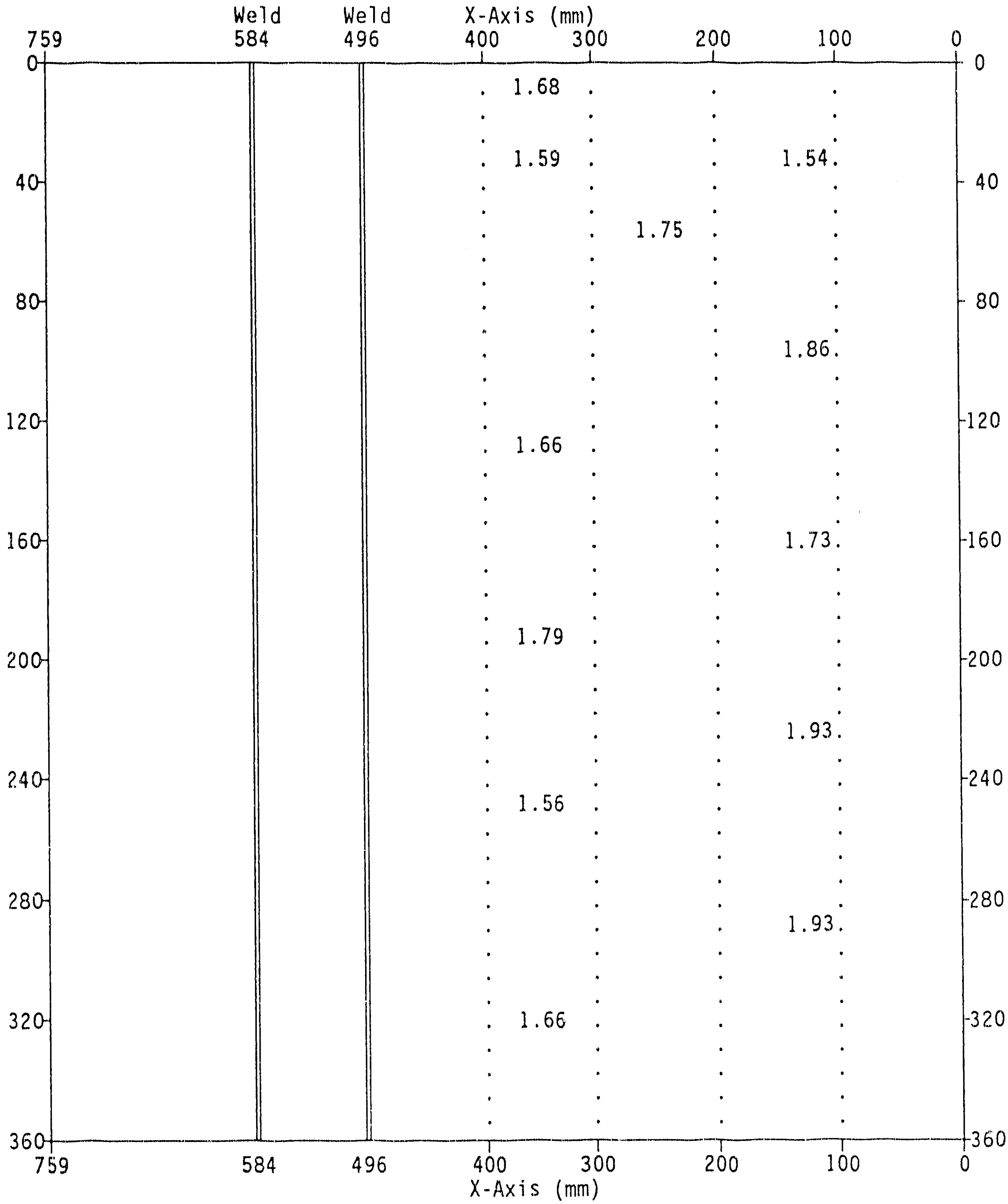


FIGURE 7. T_S/T_L Map of PISC NDW Assembly 25 (T_S/T_L = 1.7 and 1.4 for equiaxed and columnar material, respectively)

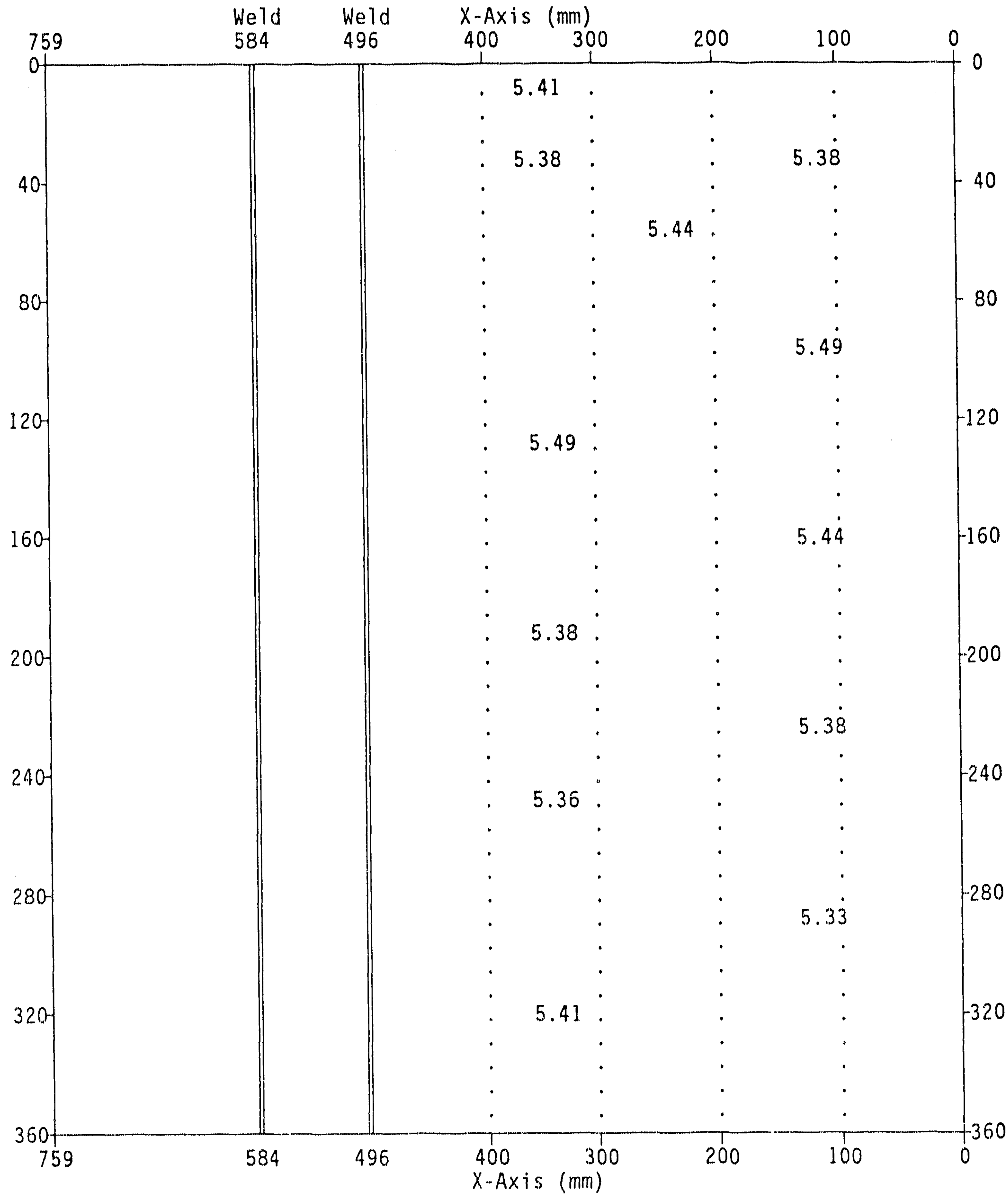


FIGURE 8. V_L Map of PISC NDW Assembly 25 (V_L = 5.84 mm/μs and 5.46 mm/μs for equiaxed and columnar material, respectively)

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11. ABSTRACT (200 words or less)

The Evaluation and Improvement of NDE Reliability for Inservice Inspection of Light Water Reactors (NDE Reliability) Program at the Pacific Northwest Laboratory was established by the Nuclear Regulatory Commission to determine the reliability of current inservice inspection (ISI) techniques and to develop recommendations that will ensure a suitably high inspection reliability. The objectives of this program include determining the reliability of ISI performed on the primary systems of commercial light-water reactors (LWRs); using probabilistic fracture mechanics analysis to determine the impact of NDE unreliability on system safety; and evaluating reliability improvements that can be achieved with improved and advanced technology. A final objective is to formulate recommended revisions to ASME Code and Regulatory requirements, based on material properties, service conditions, and NDE uncertainties. The program scope is limited to ISI of the primary systems including the piping, vessel, and other components inspected in accordance with Section XI of the ASME Code. This is a progress report covering the programmatic work from October 1990 through March 1991.

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