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

Semi-Annual Report
October 1988 - March 1989

Prepared by S. R. Doctor, J. D. Deffenbaugh, M. S. Good, E. R. Green,
P. G. Heasler, F. A. Simonen, J. C. Spanner, T. T. Taylor, T. V. Vo

Pacific Northwest Laboratory
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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 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 1988 through March 1989.

EXECUTIVE SUMMARY[a]

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 Section XI 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. Because of the problems associated with the reliable detection, correct interpretation, and accurate characterization of defects during ultrasonic testing/inservice inspection (UT/ISI) of piping, the major efforts during this reporting period were concentrated in the Piping task and the New Inspection Criteria task. However, some work was initiated on the Pressure Vessel Task.

The major highlights during this reporting period were:

- <u>ASME Code Activity</u>

  Participation in ASME Section XI activities continued toward achieving Code acceptance of NRC-funded PNL research to improve the reliability of nondestructive evaluation/inservice inspection (NDE/ISI). Appendix VII on Personnel Training and Qualification received final Code approval and was published in the 1988 Addenda to ASME Section XI. The proposed

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(a) RSR FIN Budget No. B2289; RSR Contact: J. Muscara

Appendix VIII on UT/ISI Performance Demonstration was approved by the Section XI Subcommittee and the ASME Main Committee, and has been submitted for BNCS letter ballot.

- Pressure Vessel Inspection

Analysis of PISC-II Data. The objective of this task is to determine U.S. ultrasonic inspection capability on reactor pressure vessels using PISC-II data. Probability of detection (POD) capabilities for the inspection procedures used during the PISC-II round robin were evaluated during this reporting period. Analysis of the PISC-II data revealed the extent to which flaw detection was affected by the inspection and material variables. The POD performance for the U.S. teams appeared to be slightly less consistent than the non-U.S. teams. The team-to-team differences in POD performance were significant.

Logistic regression analysis was applied to determine which of the three flaw size parameters (flaw length, flaw depth, or flaw cross-sectional area) best correlated with POD. It was found that flaw length was the most effective in explaining POD in thick-section components, flaw depth was next, and flaw cross-sectional area was less effective.

Equipment Interaction Matrix. This work is directed towards evaluation of the effects of frequency domain equipment interactions and determination of tolerance values for improving ultrasonic inspection reliability. An analysis is being performed to evaluate frequency domain effects using a computer model to calculate the flaw transfer function.

The work performed during this reporting period was directed primarily toward providing a case for the important finding of the last reporting period (Doctor et al. 1989b) -- the center frequency tolerance in ASME Code Case N-409-1 is too broad to ensure adequate measurement repeatability and thus reliable ultrasonic inspection when inspecting worst-case flaws with narrow-band UT/ISI systems. The activities included:

- Adequate measurement repeatability was defined as ±2 dB, and the model results were re-evaluated using this criterion, but the results were the same -- the N-409-1 center frequency tolerance is too broad to ensure adequate measurement repeatability when inspecting worst-case flaws with narrow-band UT/ISI systems.

- A search of the ultrasonics literature was performed to identify the worst-case defects with respect to equipment parameter sensitivity, and a paper on this subject was submitted for publication to obtain peer review. In the literature examined, no defects were found which would be worse for equipment interaction than those considered in this project's sensitivity studies.

- Model results on center frequency sensitivity were experimentally confirmed: the N-409-1 center frequency tolerance is too broad.

- New Inspection Criteria

  Work continued on assessing the adequacy of existing ASME Code requirements for ISI and on developing technical bases for improving these requirements to assure safe nuclear power plant operation. Calculations during this reporting period have applied probabilistic risk assessment (PRA) to establish inspection priorities for pressure boundary systems and components. Plant specific PRA studies have been completed for four plants (Oconee-3, Surry-1, Calvert Cliffs-1, and Crystal River-3), and four more sample plants have been selected for future evaluations. Results show a substantial range in the inspection requirements for different safety related systems within a given plant. However, the inspection priorities remain relatively constant for similar systems in different plants even for plants designed by different PWR reactor vendors.

  Development of a comprehensive probabilistic approach for improved inspection requirements continued. These efforts have focused on participation in a newly formed ASME Research Task Force on Risk-Based Inspection Guidelines. An evaluation of data on piping service failures has been completed. The objective was to apply knowledge gained from plant operating histories as a guide for future piping inspections. The data also provided insight into the successes and failures of past programs for inservice inspection. Results indicate a mixed record of success in finding defects through inservice inspection programs. While many defects have been detected during scheduled ISI, the most common method of discovering defects has been through incidental observations of leakage.

- 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: mini-round robin report, piping inspection round robin report, qualification document, surface roughness, field pipe characterization, and PISC-III activities.

  MRR Report. The Mini-Round Robin (MRR) subtask was conducted to provide an engineering data base for UT/ISI that would help: a) quantify the effect of training and performance demonstration testing required by IEB 83-02, b) quantify the differences in capability between detecting long versus short cracks, and c) quantify the capability of UT/ISI technicians to determine length and depth of intergranular stress corrosion cracks (IGSCC). A NUREG/CR report, prepared to document the work conducted under this subtask, was submitted for NRC review. Work is in progress to accomplish the revisions necessary to address technical issues and accommodate NRC review comments. A paper entitled "An Evaluation of Ultrasonic Inspection for Intergranular Stress Corrosion Cracks through Round-Robin Testing" was accepted for publication in Materials Evaluation.

Qualification Criteria for UT/ISI Systems. The objective of this subtask is to improve the reliability of UT/ISI through the development of new criteria and requirements for qualifying UT/ISI systems. Technical issues have been identified and addressed, and this document was revised and submitted for NRC review. Additional NRC comments were received, and the document is undergoing additional revision to accommodate these latter comments.

Surface Roughness. The objective of this subtask is to establish specifications such that an effective and reliable ultrasonic inspection is not prevented by the condition of the inspection surface. This is a cooperative effort with the Center for NDE (CNDE) and PNL proposed a matrix of surface conditions and ultrasonic inspection parameters for this task. Furthermore, data on use of a longitudinal-wave microprobe to generate UT field maps has been developed to draft an article for submission to a technical journal.

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. A specimen set has been prepared for shipment to Europe for use in PISC-III program studies; however, actual shipment has been deferred pending resolution of a problem that arose because of limited capabilities at the Joint Research Centre, Ispra, Italy in being able to handle highly radioactive specimens and is not resolved.

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); providing five safe-ends from the Monticello plant; providing a sector of the Hope Creek reactor pressure vessel containing two recirculation system inlet nozzles; coordination of the inspections to be conducted by U.S. teams on the various actions; and input to the studies on reliability and specimens for use in the parametric, capability, and reliability studies of the AST. Planning continued on the specimens for the AST with all the wrought stainless steel specimens for the capability studies being identified. U.S. companies were contacted to coordinate the inspections to be performed by them on the three dissimilar metal weld PISC-III samples that were to come to the U.S. between April and September 1989.

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NONDESTRUCTIVE EXAMINATION (NDE) RELIABILITY
FOR INSERVICE INSPECTION OF LIGHT WATER REACTORS

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 light-water 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 ASME Code and the Regulatory 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. Because of the problems associated with the reliable detection and accurate characterization of defects during ultrasonic testing/inservice inspection (UT/ISI) of piping, the major efforts were concentrated in the Piping task and the New Inspection Criteria task. However, work was conducted on the Pressure Vessel Task and will be receiving greater emphasis in future reporting periods.

This report is divided into the following sections.

- ASME Code Related Activities
- Pressure Vessel Inspection
- New Inspection Criteria
- 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 to improve the reliability of nondestructive evaluation/inservice inspection (NDE/ISI). Appendix VII on Personnel Training and Qualification received final Code approval and was published in the 1988 Addenda to ASME Section XI. The proposed Appendix VIII on UT/ISI Performance Demonstration was approved by the Section XI Subcommittee and the ASME Main Committee, and has been submitted for BNCS letter ballot.

2.2 INTRODUCTION

The objective of this task is to develop and/or evaluate new criteria and requirements for qualifying ultrasonic testing/inservice inspection (UT/ISI) and other NDE/ISI systems. The ultimate goal is for these criteria and requirements to be incorporated into Section XI of the ASME Boiler and Pressure Vessel Code. If that goal cannot be met, or if the requirements adopted by ASME Section XI (SC-XI) are inadequate, PNL may also prepare draft Regulatory Guide input as a back-up approach. A NUREG report (NUREG/CR-4882) is being prepared to document the criteria and requirements developed to date, as well as to document the background and rationale associated with these activities.

The "Proposed Appendix VII" developed in 1986 by an ASME Ad Hoc Task Group has been extensively restructured and revised by the SC-XI SGNDE. This Ad Hoc Task Group document was restructured as two companion mandatory appendices for incorporation into Section XI of the ASME Code. For convenience, these two appendices are identified herein as a) Appendix VII on Personnel Training and Qualification and b) Appendix VIII on UT System Performance Demonstrations. Additionally, administrative assistance is provided in support of related efforts to achieve Code acceptance and publication of a proposed Code Case on acoustic emission and a rewrite of Appendix IV to accommodate the multifrequency eddy current equipment currently being used for ISI of steam generator tubes.

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 to improve the reliability of NDE/ISI. During this reporting period, ASME Section XI Code meetings were held October 24-27, 1988 in Albuquerque, New Mexico and January 16-19, 1989 in Salt Lake City, Utah. Agendas and minutes of SGNDE meetings held in conjunction with Section XI Subcommittee meetings were prepared and distributed. J. C. Spanner serves as Secretary of the SGNDE and as a member of the Working Group on Surface Examination and Personnel Qualification. T. T. Taylor chairs a Special Task Group to develop acoustic emission criteria and requirements, and serves as a member of the Working Group on Volumetric Examination and Procedure Qualification. PNL staff gave technical presentations to various SC-XI groups on: a) new inspection criteria and b) acoustic emission technology.

Appendix VII on Personnel Training and Qualification was formally approved by the Main Committee (M.C.) and the Board on Nuclear Codes and Standards (BNCS). Four negatives were received from the initial BNCS letter ballot on Appendix VII, and a technical response was prepared to address the concerns raised in these negative ballots. The proposed Appendix VII received final BNCS approval on a second consideration letter ballot, and this document was subsequently published in the Winter 1988 Addenda to Section XI.

The proposed Appendix VIII on UT/ISI Performance Demonstrations was approved by SC-XI for submittal to the Main Committee. Both Section V representatives submitted negative votes during the initial M.C. consideration of this document. A technical response to these negatives was prepared, and selected SGNDE personnel (including a PNL representative) attended the Section V meeting in February in an attempt to resolve these problems. This liaison effort was successful, and both SC-V representatives withdrew their negative votes during the next M.C. meeting. Hence, Appendix VIII has now received M.C. approval and is being submitted for BNCS letter ballot.

Appendix VIII includes essentially all of the provisions of Code Case N-409-2, plus it extends the performance demonstration concept to other Section XI applications such as the clad/base metal interface of pressure vessel shell welds, nozzle inner radius areas, pressure vessel shell welds other than the clad/base metal interface, nozzle-to-shell welds, and bolting and studs. When adopted and published in the ASME Code, this appendix will represent a significant enhancement in the performance demonstration requirements for all of the key Section XI ultrasonic testing applications. It could also provide a basis for extending the concept of performance demonstrations to the other NDE/ISI methods required by ASME Section XI.

PNL staff have been assigned to a task group responsible for re-evaluating the current Section XI visual acuity requirements, and work on this task continues.

Proposed new Section XI criteria and requirements for applying the acoustic emission method for selected Section XI applications have been developed. A proposed new Code Case on acoustic emission was approved by SC-XI for submittal to the M.C. This Code Case is entitled "Acoustic Emission for Successive Inspections Required by Section XI, Division 1," and was considered by the M.C. during their February meeting. Both Section V representatives, and the National Board representative, voted negative on this document. A variety of changes were incorporated into the document, and detailed letters were prepared, in response to the concerns expressed by the M.C. negators. Reapproval of this Code Case (including the latest revisions) will be sought during the next scheduled SGNDE and SC-XI meetings.

2.4 FUTURE WORK

In preparation for the next Section XI meetings to be held April 10-13, 1989 in Portland, Oregon, revisions to the proposed Code Case "Acoustic Emission for Successive Inspections Required by Section XI, Division 1" were developed and finalized copies of this document were distributed. Assuming that the proposed Code Case on acoustic emission ISI is approved by the M.C. during either the May or September meetings, the next, and final, step for this document is BNCS consideration. It is expected that additional PNL staff effort will be required to accommodate the additional difficulties this document may yet encounter.

If the first consideration BNCS letter ballot on the proposed Appendix VIII on UT/ISI Performance Demonstrations is successful, most of the PNL work on this document will have been completed; however, if any negatives are cast on the BNCS ballot, PNL staff will prepare appropriate response letters, proposed revisions, or both. Work continues on drafting generic sizing requirements for Supplement 12 of Appendix I and on supplements to Appendix VIII to address cast stainless steel components and dissimilar metal welds.

In his role as SGNDE Secretary, J. C. Spanner prepares and distributes the agendas and minutes for all SGNDE meetings. These are drafted immediately following each meeting, and are then finalized and distributed to the approximately 60 recipients on the SGNDE mailing list 4-6 weeks prior to each Section XI meeting. Future Section XI meetings will be held in Portland, Oregon April 10-13, 1989; Boston, Massachusetts August 28-31, 1989; and Orlando, Florida November 6-9, 1989.

3.0 PRESSURE VESSEL INSPECTION

3.1 ANALYSIS OF PISC-II DATA

3.1.1 Summary

The objective of this task is to determine U.S. ultrasonic inspection capability on pressure vessels from PISC-II data. Probability of detection capabilities for the inspection procedures used in the PISC-II round robin were evaluated during this reporing period.

3.1.2 Introduction

Data were obtained from an international round-robin test of ultrasonic inspection capability that was conducted under PISC-II (Programme for the Inspection of Steel Components). These inspection data were gathered using four heavy-section steel components consisting of two plates and two nozzle configurations. Teams from several European countries as well as the U.S. and Japan participated in this multi-year study.

The NDE Reliability Program is using this data base to extract information that is relevant to inservice inspection in the U.S. Inspection capability is evaluated using statistical procedures that account for experimental error in measurements made during the round robin. Specific topics relevant to U.S. inspection capability that will be dealt with in this task include:

- Analysis of U.S. team performance compared to overall team performance.
- Analysis of team performance with respect to the requirements of ASME Section XI, Appendix VIII for both detection and sizing.
- Assess the inspection techniques used in PISC-II for possible use in U.S. pressure vessel inspections.

3.1.3 Status of Work Performed

During this reporting period, PNL completed approximately one-half of the analysis called for under this task. First, the ultrasonic indications were associated with cracks using a computer "scoring" algorithm so that detection statistics could be computed. Second, the derived detection statistics were used to evaluate probability of detection performance for the inspection procedures. These results were compiled into two sections of a report intended to summarize all results from this task.

Analysis of PISC-II data revealed the extent to which flaw detection was affected by the inspection and material variables. This evaluation was conducted using Probability of Detection (POD) tabulations and logistic regression curves. The χ-squared statistic was divided by its degrees of freedom to rank the variables with respect to importance in influencing POD. The result was that "flaw type" and "procedure" were the most important variables, and "flaw location" (i.e., clad/parent metal) and "country" (U.S./non-U.S.) were at the bottom of the ranking but were still significant. Notably, "flaw type" led all other variables in importance by a significant margin.

The flaws within the clad region were, on average, smaller than those in the base metal regions; and a few were much larger than any of the clad region flaws. This factor, combined with the inherent difficulty of UT inspection of coarse-grained cladding material and the fact that few inspectors used procedures designed to detect flaws in cladding, suggested that the POD values would tend to be worse for flaws in cladding than in base metal. Not surprisingly, the POD values were consistent with this hypothesis. For example, a manual technique using a 10% DAC (manual-10% DAC) threshold produced a base metal POD that was approximately twice the POD for the clad region.

Although "country" (U.S. versus non-U.S. teams) was the least significant variable (i.e., the difference in POD between U.S. and non-U.S. teams was quite small), and interesting patterns may exist between these two groups of teams. The POD performance for the U.S. teams appeared to be slightly less consistent than the non-U.S. teams. Further work dealing with false call probabilities and sizing performance is in progress.

Logistic regression analysis was applied to determine which of three flaw size parameters best correlated with POD. The flaw size parameters examined were: 1) flaw length, 2) flaw depth, and 3) cross-sectional area of flaw (length times depth). Goodness-of-fit statistics were used to determine if the logistic regression satisfactorily explained the variability in the POD data. On this basis, it was found that flaw length was the most effective in explaining POD in thick-section components, flaw depth was next, and flaw cross-sectional area was least effective. Linear combinations of both depth and length were also examined, but this did not produce an equation that fit the POD data better, or was more reasonable, than either simple length, depth, or cross-sectional area.

3.1.4 Future Work

During the next six months, the sizing performance of the inspection procedures will be examined, using regression analysis. Pa.ticular attention will be paid to the distributional properties of the sizing errors. Also planned is an evaluation of the pass/fail criteria for detection performance that was recently adopted in Appendix VIII of the ASME Boiler and Pressure Vessel Code.

Completion of this evaluation will also allow us to complete a report on the PISC-II data re-analysis.

3.2 EQUIPMENT INTERACTION MATRIX

3.2.1 Summary

This work is directed towards evaluation of the effects of frequency domain equipment interactions and determination of tolerance values for improving ultrasonic inspection reliability. An analysis is being performed to evaluate frequency domain effects using a computer model to calculate the flaw transfer function.

The work performed during this reporting period was directed primarily toward providing a case for the important finding of the last reporting period (Doctor et al. 1989b) -- the center frequency tolerance in ASME Code Case N-409-1 is too broad to ensure adequate measurement repeatability and thus reliable ultrasonic inspection when inspecting worst-case flaws with narrow-band UT/ISI systems. The activities included:

- Adequate measurement repeatability was defined as ±2 dB, and the model results were re-evaluated using this criterion, but the results were the same -- the N-409-1 center frequency tolerance is too broad to ensure adequate measurement repeatability when inspecting worst-case flaws with narrow-band UT/ISI systems.

- A search of the ultrasonics literature was performed to identify the worst-case defects with respect to equipment parameters sensitivity, and a paper on this subject was submitted for publication to obtain peer review. In the literature examined, no defects were found which would be worse for equipment interaction than those considered in this project's sensitivity studies.

- Model results on center frequency sensitivity were experimentally confirmed. The N-409-1 center frequency tolerance is too broad.

3.2.2 Introduction

The goal of this work is to define operating tolerance requirements for UT/ISI equipment that minimize 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. The current specifications are based on engineering judgement and lack a solid analytical foundation. The Interaction Matrix Study will provide this foundation. Both thin sections (piping) and thick steel sections (pressure vessels) are being evaluated.

The following work was completed during previous reporting periods:

- Mathematical models were developed for UT/ISI equipment. This work was presented for peer review at the 1986 QNDE conference (Mart and Doctor 1987).

- A mathematical model was developed to calculate the transfer functions (frequency responses) for 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 the 1988 QNDE conference (Green and Mart 1989).

- Equipment bandwidth and center frequency sensitivity studies were performed for thin sections (piping) using calculated worst-case flaw transfer functions. An abstract for a paper on this subject has been submitted for the 1989 QNDE conference. It was found that ASME Code Case N-409-1 bandwidth tolerances are sufficient to ensure reliable inspection, but the center frequency tolerances are not adequate to ensure reliable inspection of certain calculated worst-case flaws with narrow-band UT/ISI systems.

3.2.3 Status of Work Performed

Sensitivity Studies. Adequate measurement repeatability was defined as ±2 dB, and the model results were re-evaluated using this criterion. Review of the original results (Doctor et al. 1989b) revealed several inadequacies, so the ultrasonic equipment bandwidth and center frequency sensitivity studies were repeated. The study was improved in three ways: 1) more data points were used to make each sensitivity curve (the curves were made previously with only six points, and there was some question as to what was happening between the plotted values); 2) the results were plotted in a log-log format so that the sensitivity of the equipment in dB per percent change in the parameter value could be judged directly from the slope of the curve rather than by comparison with superimposed curves for each dB per percent change value; and 3) the repeatability criterion was changed from ±10% to ±26% (±2 dB). While there are no Code standards for measurement repeatability, it was felt that ±2 dB would be considered to be a reasonable repeatability by the inspection community at large.

The results of the equipment bandwidth sensitivity study for the seven computed worst-case defect transfer functions are presented in Figure 3.1. They indicate that a bandwidth change of 10% would produce a calibrated echo response change of less than 2 dB. If the bandwidth tolerance was relaxed from its current Code value of ±10% to a less conservative value of ±20%, a ±2 dB repeatability could still be maintained according to this model.

The results of the revised equipment center frequency sensitivity study for the worst-case flaws are shown in Figures 3.2 through 3.8. These results show that the center frequency sensitivity may be a worse problem than was suspected after the original study. The narrow-band equipment curve for worst-case defect E is particularly bad -- at its worst point, a change in equipment center frequency of 10% would produce a response change of over 8 dB (250%). Of course, this result was obtained with a calculated rather than a measured flaw transfer function. As described below, experiments were conducted to determine if measured transfer functions can be as bad as the worst-case transfer function calculated by the model.

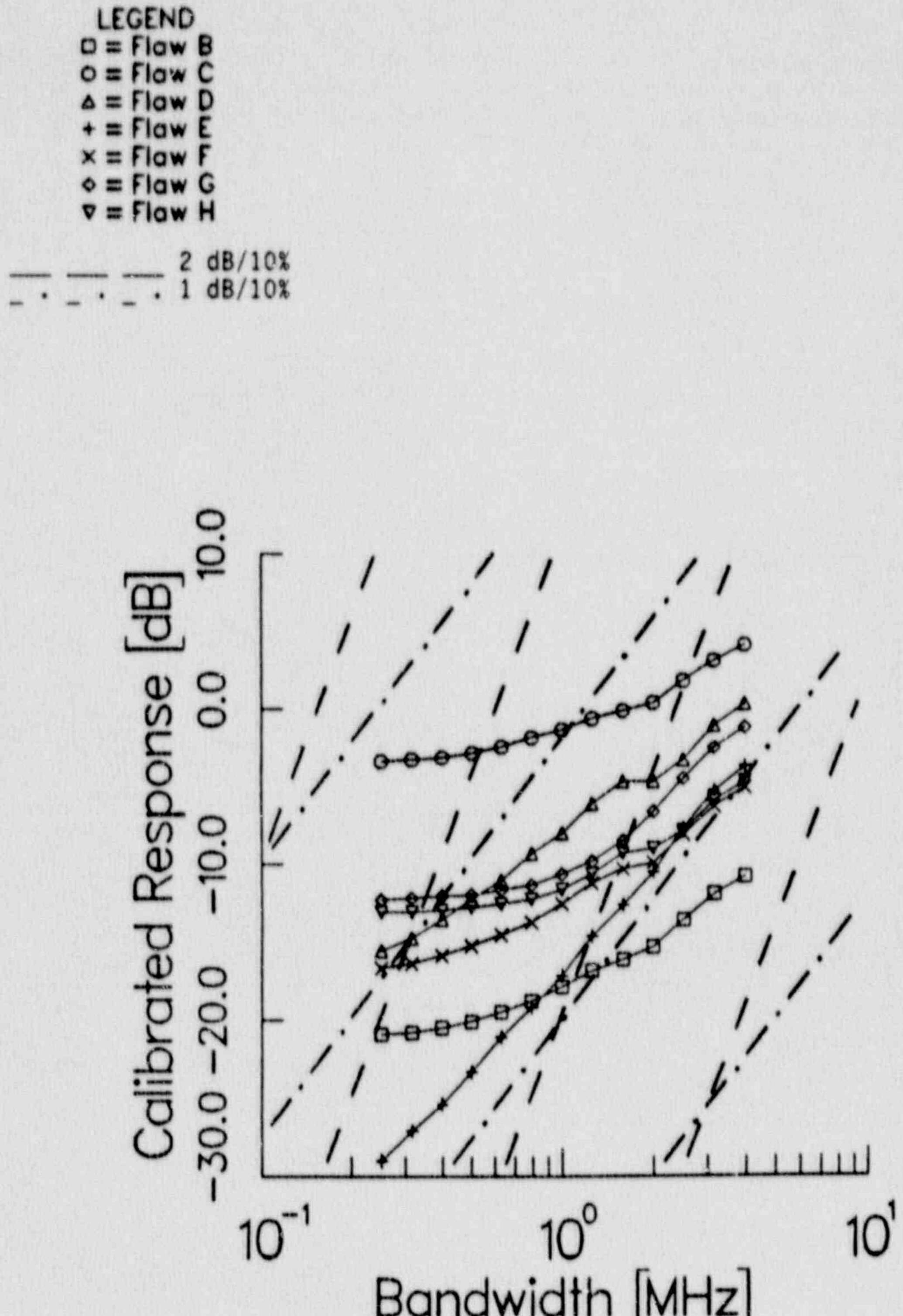

FIGURE 3.1. Effect of Equipment Bandwidth Changes on the Echo Response from Seven Hypothetical Worst-Case Defects

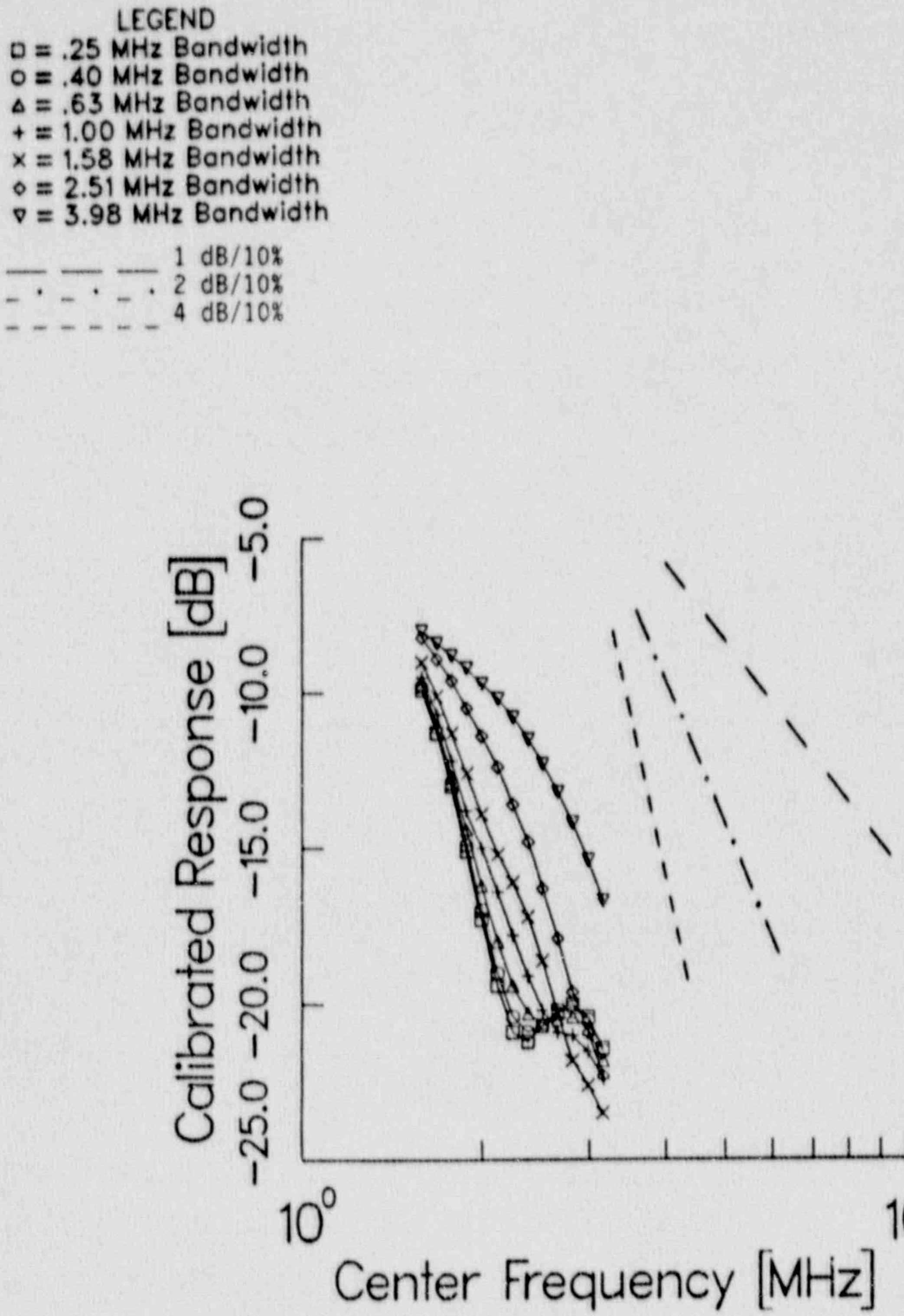

FIGURE 3.2. Effect of Equipment Center Frequency Changes on the Echo Response from Worst-Case Defect B for Various Bandwidths of Equipment

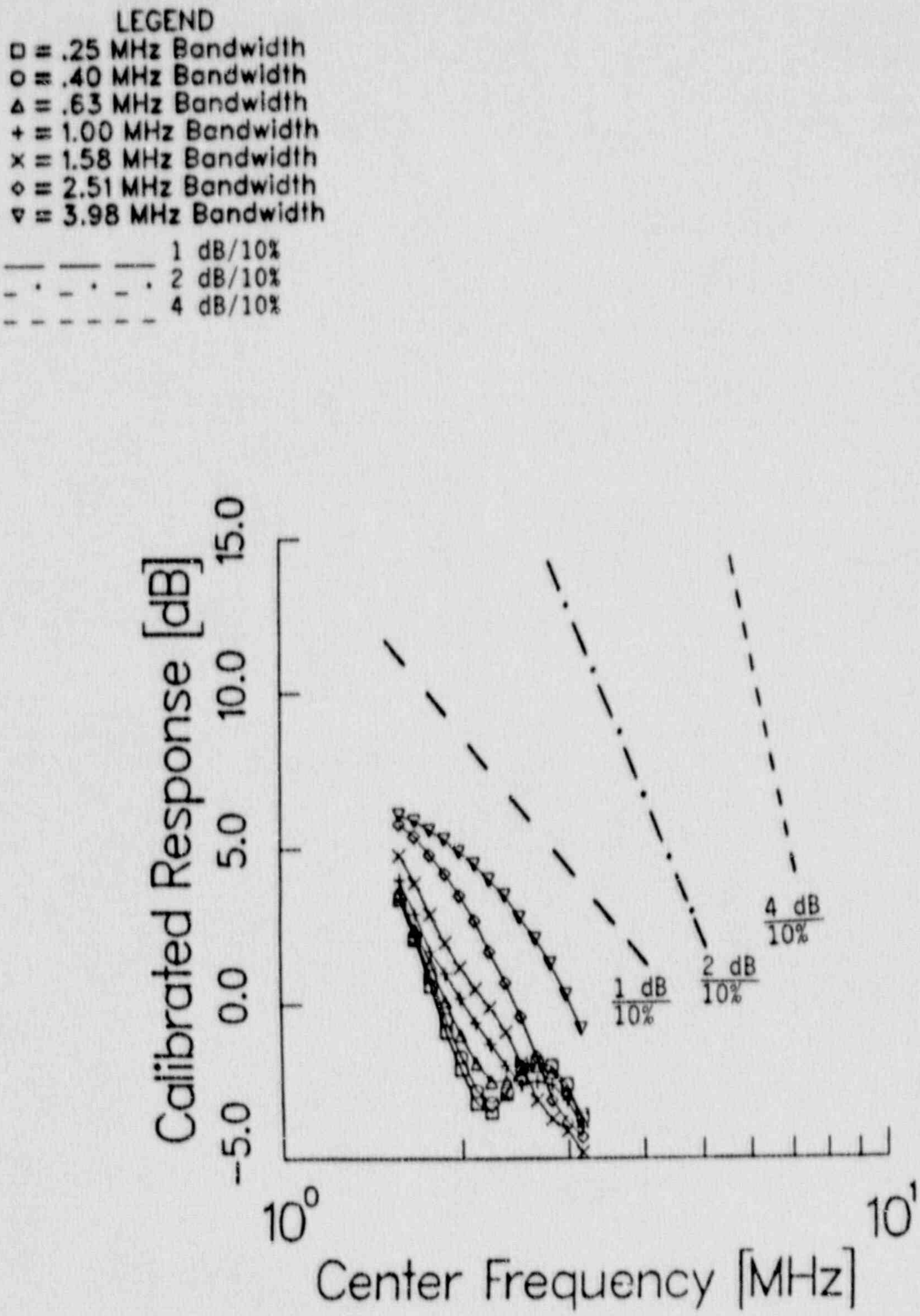

FIGURE 3.3. Effect of Equipment Center Frequency Changes on the Echo Response from Worst-Case Defect C for Various Bandwidths of Equipment

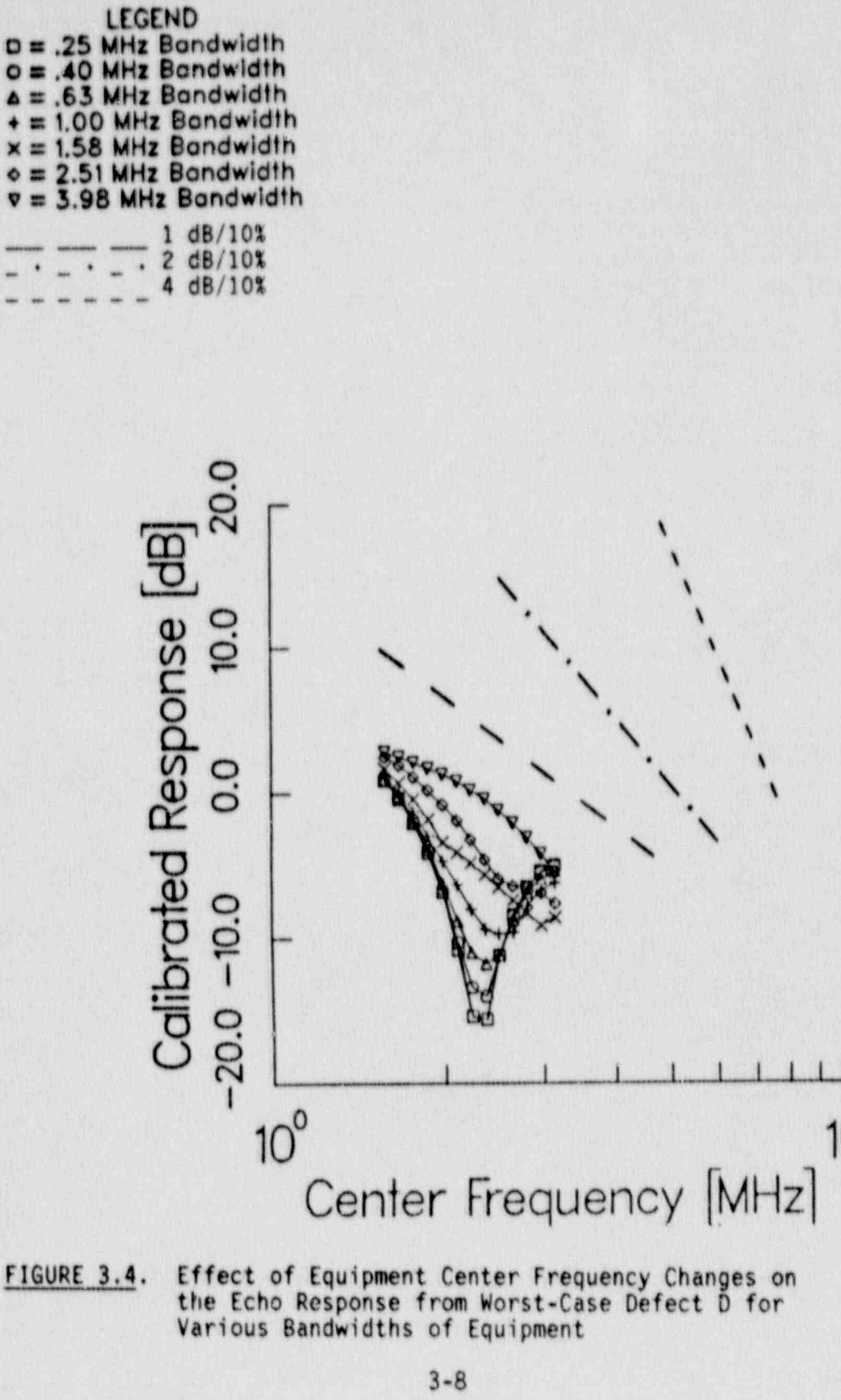

FIGURE 3.4. Effect of Equipment Center Frequency Changes on the Echo Response from Worst-Case Defect D for Various Bandwidths of Equipment

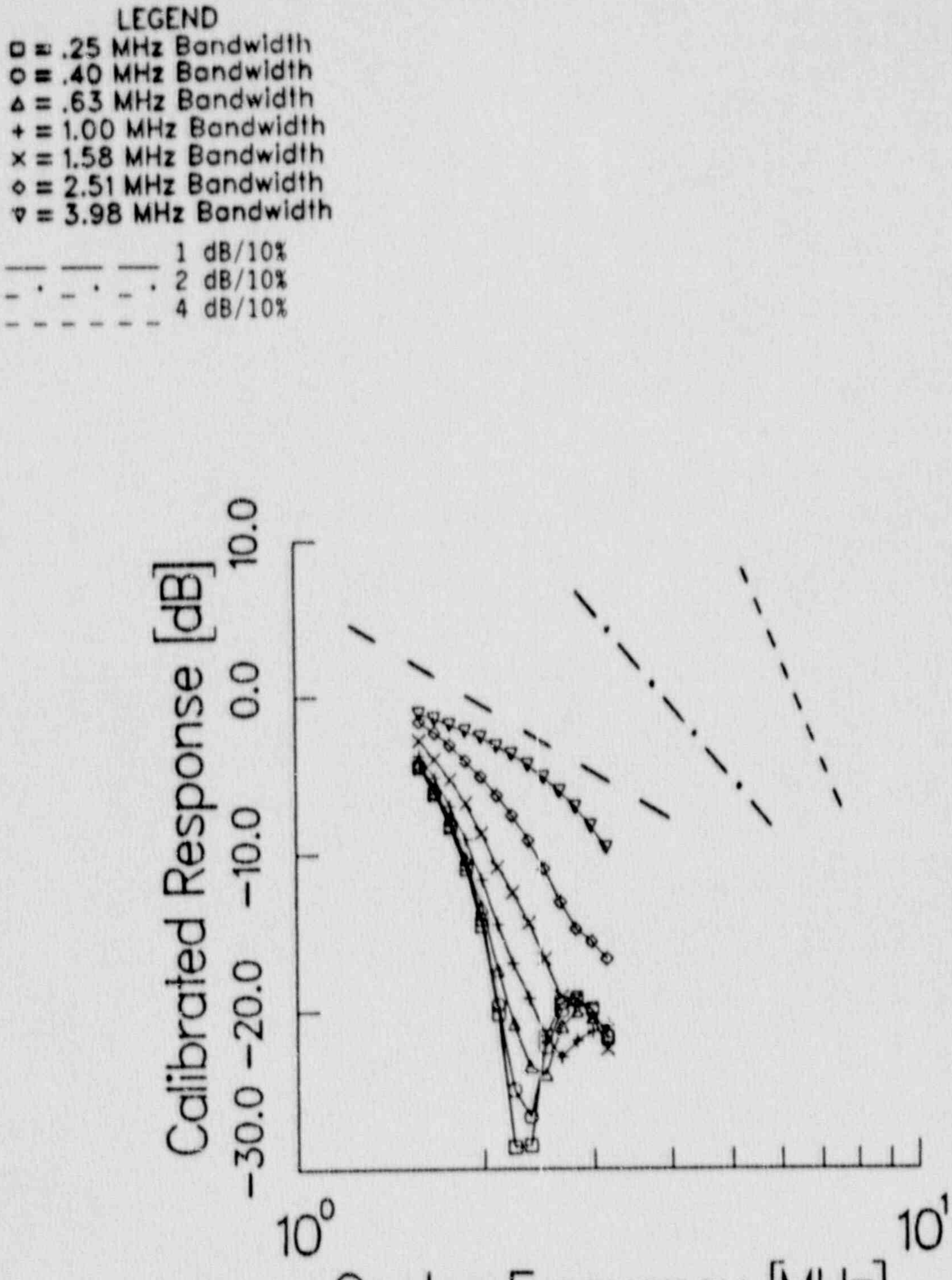

FIGURE 3.5. Effect of Equipment Center Frequency Changes on the Echo Response from Worst-Case Defect E for Various Bandwidths of Equipment

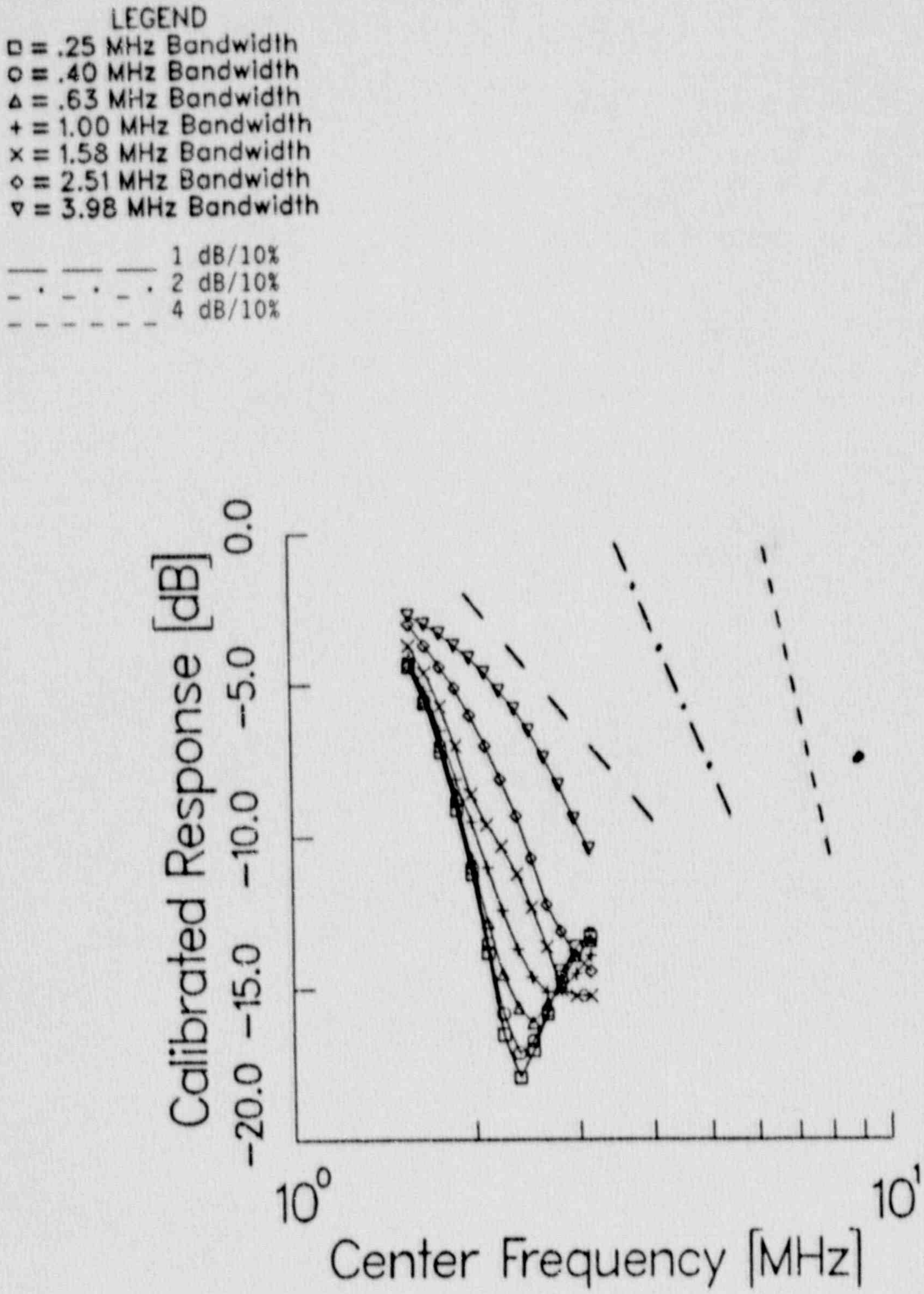

FIGURE 3.6. Effect of Equipment Center Frequency Changes on the Echo Response from Worst-Case Defect F for Various Bandwidths of Equipment

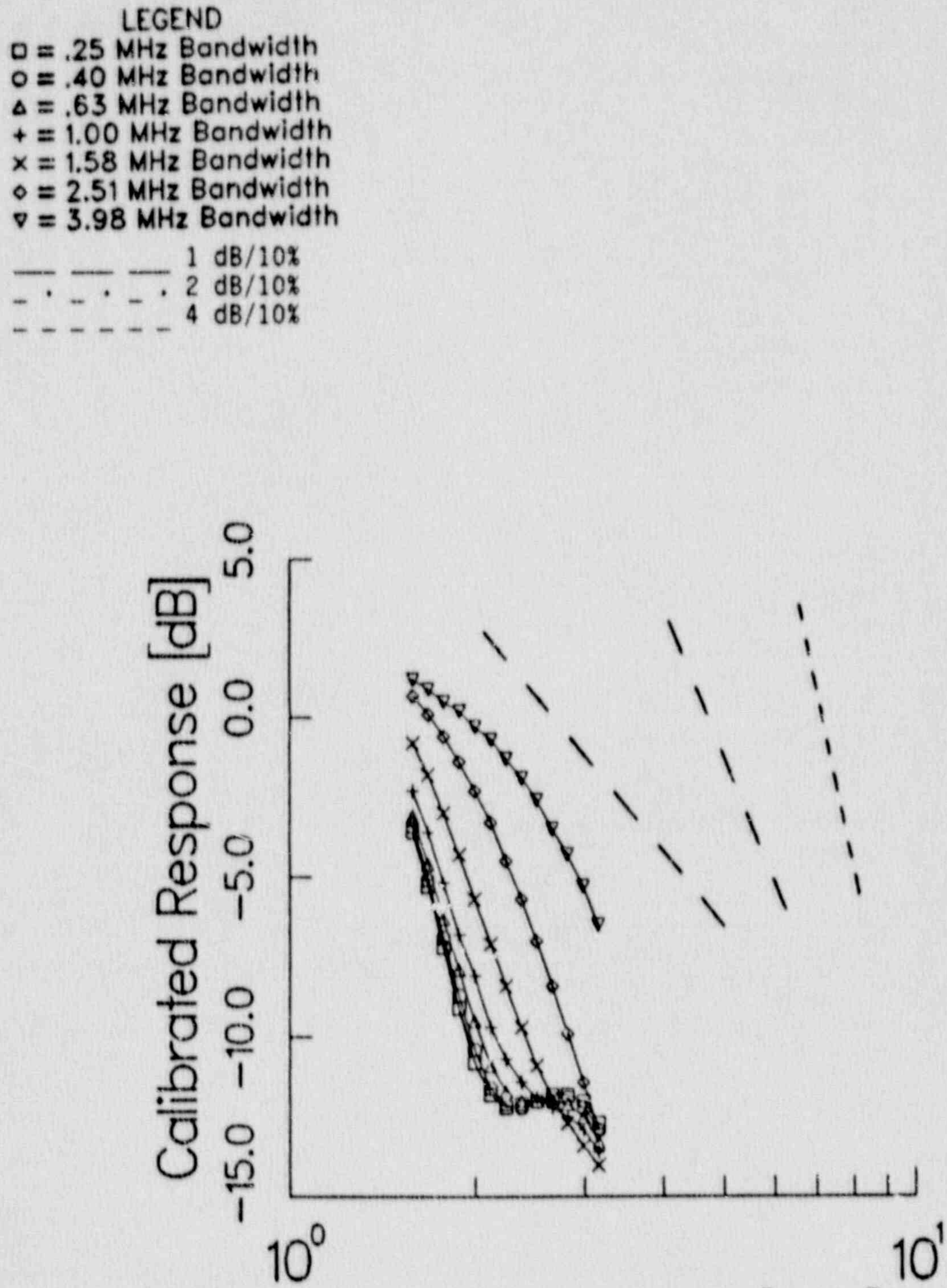

FIGURE 3.7. Effect of Equipment Center Frequency Changes on the Echo Response from Worst-Case Defect G for Various Bandwidths of Equipment

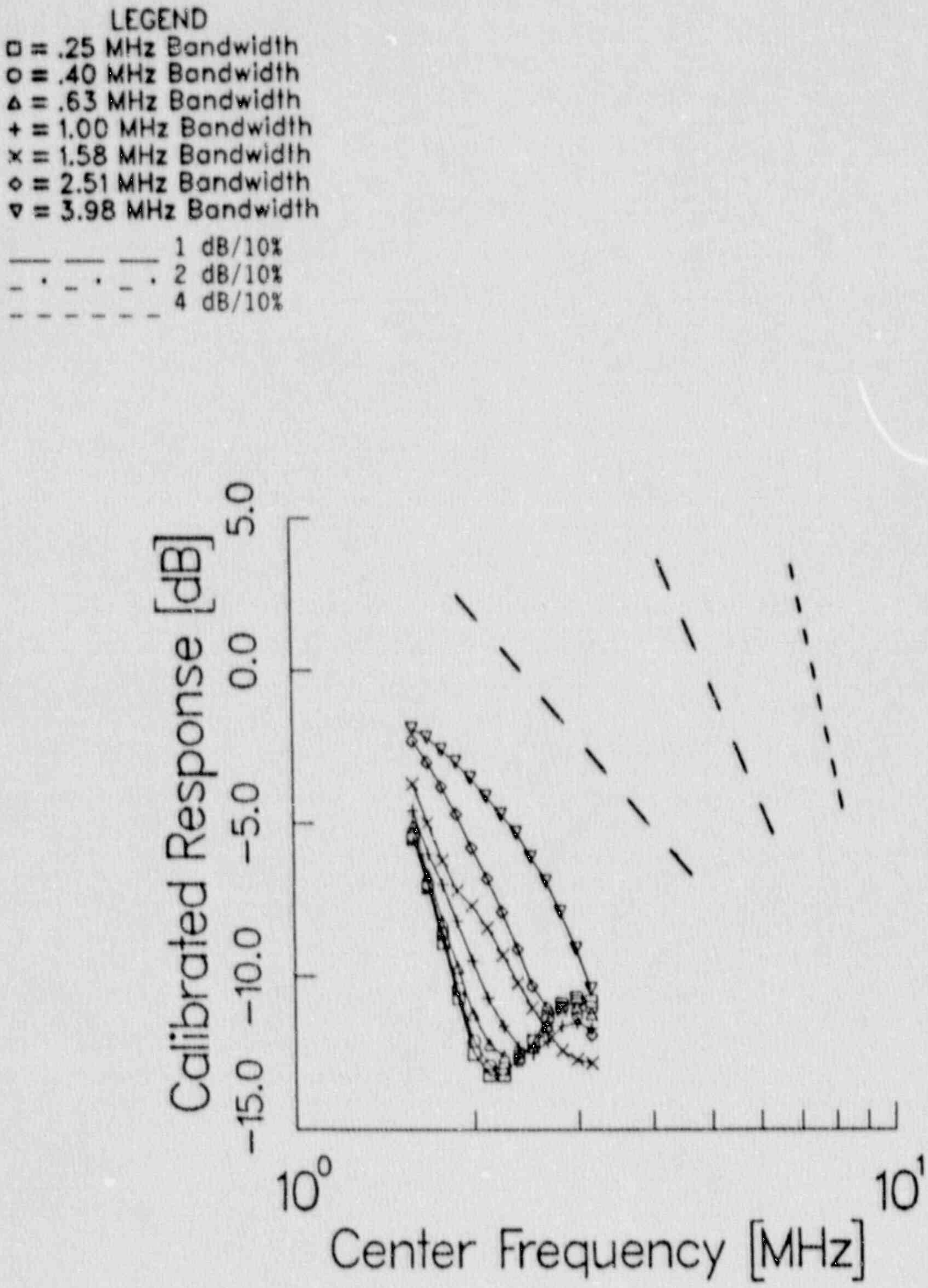

FIGURE 3.8. Effect of Equipment Center Frequency Changes on the Echo Response from Worst-Case Defect H for Various Bandwidths of Equipment

Worst-Case Defects. A thorough search of the ultrasonics literature was performed to identify the worst-case defects with respect to sensitivity to equipment parameters, and a paper on this subject entitled "Worst-Case Defects Impacting Ultrasonic Inspection Reliability" was submitted to *Materials Evaluation* (Green 1989) for publication in order to obtain peer review. In the paper, it was concluded that certain features of the acoustic system transfer function cause it to interact with the ultrasonic equipment system to produce a strong sensitivity to the frequency-domain characteristics of the equipment system. These features include 1) strong low- or high-pass filtering (i.e., a steep transfer function slope) and 2) notch filtering (e.g., a transfer function amplitude shaped like a sinc function).

The above features are present in the acoustic system transfer function of several types of defects. These worst-case defect configurations include:

- Nonspecular reflection from planar defects (almost any type of crack or inclusion with distinct edges) where the Δf (spacing between the peaks in the frequency spectrum) due to interference of wavelets diffracted by the defect edges is similar to the equipment system bandwidth.

- Specular reflection from smooth, planar defects (e.g., high-cycle fatigue cracks) where the received wavefront and receiving piezoelectric element are not parallel such that phase cancellation is produced at or near the equipment system center frequency.

- Defects with periodic roughness (e.g., low-cycle fatigue cracks) that produce a strong peak in the acoustic system transfer function at or near the equipment system center frequency.

- Any defect in a strongly attenuative medium such as coarse grain stainless steel where a significant portion of the equipment system spectrum lies above the cutoff frequency of the material.

Random profile surface roughness of a defect does not result in a worst-case defect.

In the literature examined, no defects were found which would be worse for equipment interaction than those considered in this project's sensitivity studies.

Experiments. Model results on center frequency sensitivity were confirmed experimentally. In the experiment, the echo responses from seven search units of similar manufacture but with different center frequencies (1.0, 1.5, 1.8, 2.0, 2.25, and 5 MHz) was recorded. Two search units with a center frequency of 2.25 MHz were used to provide statistical data on measurement variation. The echo responses were obtained for 45° SV contact inspection of six manufactured defects including worst-case defects (those expected to have a high sensitivity to inspection system center frequency changes) and control defects (those not anticipated to be sensitive to center frequency changes). The defect specimens are described below in Table 3.1.

TABLE 3.1. Experiment Defect Specimens

Name	Type	Material	Thickness	Percent Through -Wall	Angle From Vertical
44° Al	Calibration	Aluminum	50 mm	100%	-46°*
43° Al	Control	Al	50 mm	100%	-47°
55° Al	Worst-Case	Al	50 mm	100%	-35°
90° Corner	Calibration	Stainless Steel	15 mm	100%	0°
Flaw A	Worst-Case	S.S.	15 mm	50%	+15°
Flaw B	Control	S.S.	15 mm	50%	0°
Flaw C	Worst-Case	S.S.	15 mm	33%	+10°
Flaw D	Control	S.S.	15 mm	33%	0°

* Minus sign indicates that defect is angled away from the inspection probe.

The data from this experiment is plotted as squares in Figures 3.9-3.14. A log-log format has been chosen for the plots so that the slope of a curve connecting data points represents the center frequency sensitivity in decibels per percent change in center frequency. Reference slopes are given for sensitivities of 1, 2, and 4 dB per 10% change in center frequency. A maximum allowable sensitivity of 2 dB/10% was chosen as discussed above. Examination of Figures 3.9-3.14 revealed that none of the three worst-case defects had center frequency sensitivities greater than 2 dB/10%; thus, the center frequency sensitivity of the worst-case defects tested was acceptable. The control defects displayed no significant center frequency sensitivity.

All of the search units tested were relatively broadband yielding system bandwidths of approximately 70% except the 5 MHz search unit which produced a system bandwidth of 149%. The modeling studies showed that broad-band systems are significantly less sensitive to center frequency changes than narrow-band systems. Since both types of systems are commonly used in field inspections, narrow-band system data was also required. The experimental data was artificially narrow banded to simulate the response of narrow-band systems with various center frequencies. The response was narrow banded by taking the amplitude of the response spectrum and low-pass filtering the spectrum above the system center frequency and high-pass filtering below the system center frequency. The inverse Fourier transform of the filtered spectrum was taken to get the artificially narrow-banded time response. Filter slopes of 90 and 130 dB/decade were used, resulting in system bandwidths of approximately 28 and 19%, respectively.

The artificially narrow-banded results are plotted as circles and triangles in Figures 3.9-3.14. The center frequency sensitivities of the 55° Al block and Flaw A increase significantly with narrow banding. The center frequency sensitivity for the narrow-band systems is approximately 4 dB/10% which is unacceptable per the 2 dB/10% limit that has been adopted for this work.

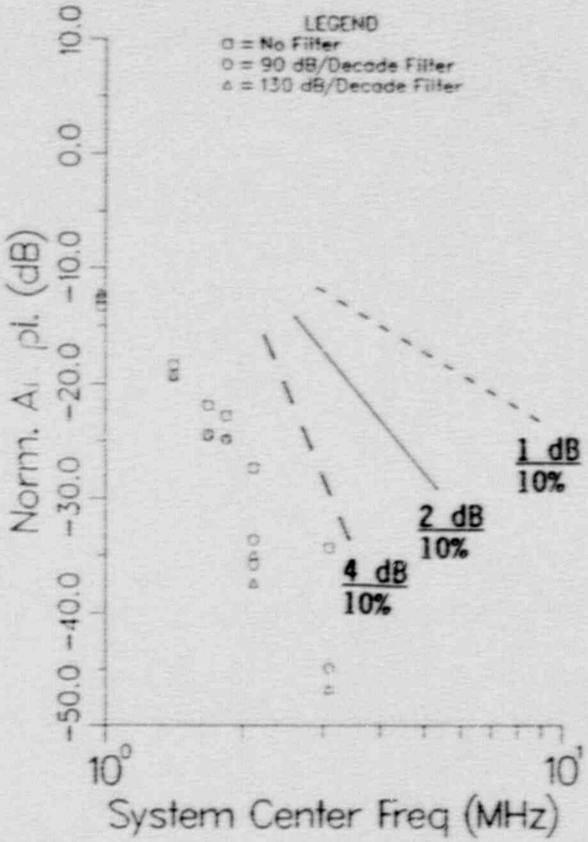

FIGURE 3.9. Center Frequency Experiment Results for the 55° Al Worst-Case Defect Sample with and without Artificial Narrow Band Filtering

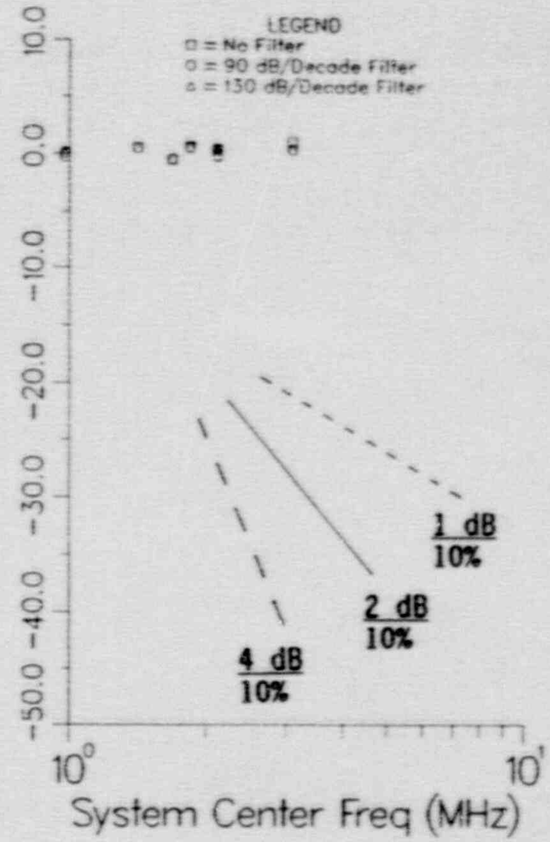

FIGURE 3.10. Center Frequency Experiment Results for the 43° Al Control Sample with and without Artificial Narrow Band Filtering

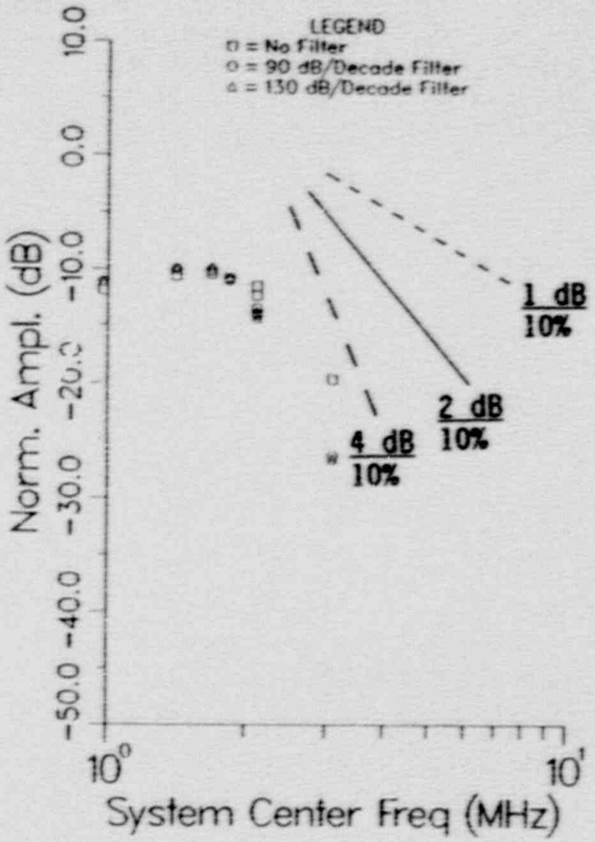

FIGURE 3.11. Center Frequency Experiment Results for the Flaw A Worst-Case Defect Sample with and without Artificial Narrow Band Filtering

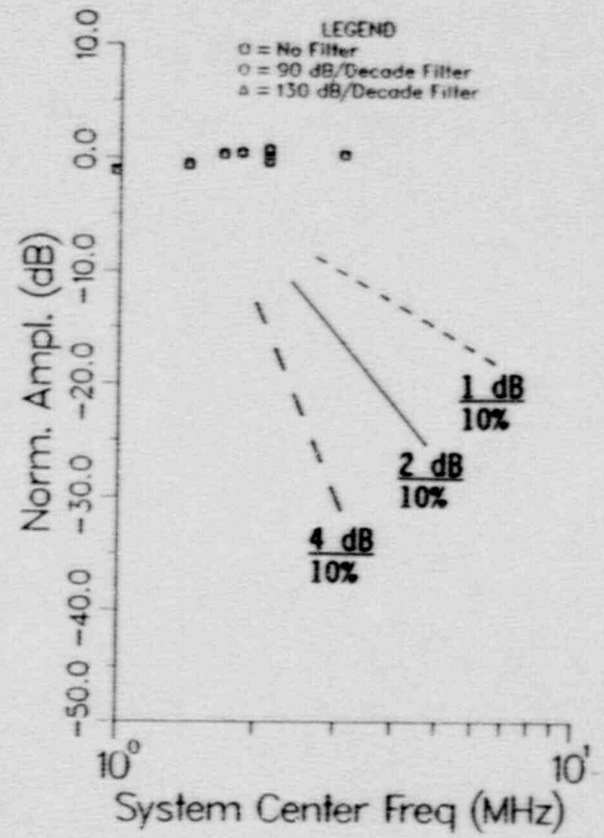

FIGURE 3.12. Center Frequency Experiment Results for the Flaw B Control Sample with and without Artificial Narrow Band Filtering

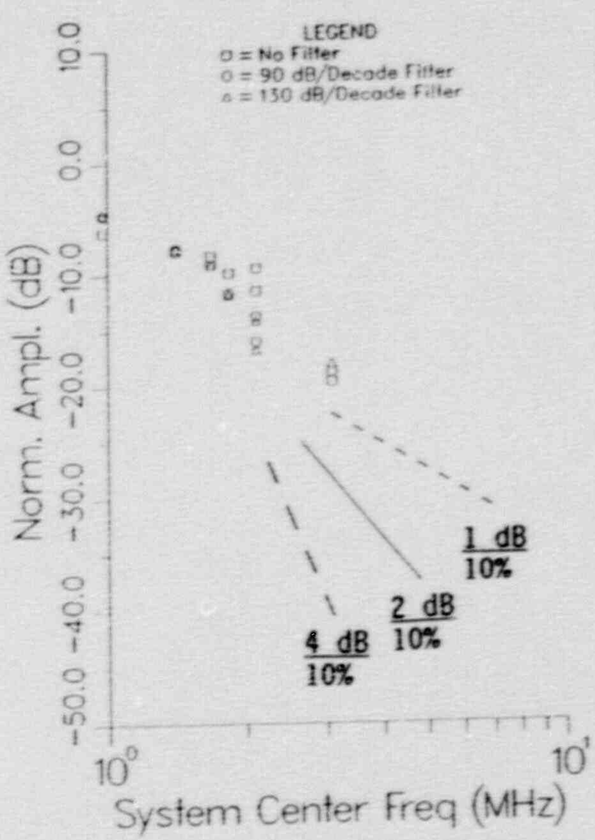

FIGURE 3.13. Center Frequency Experiment Results for the Flaw C Worst-Case Defect Sample with and without Artificial Narrow Band Filtering

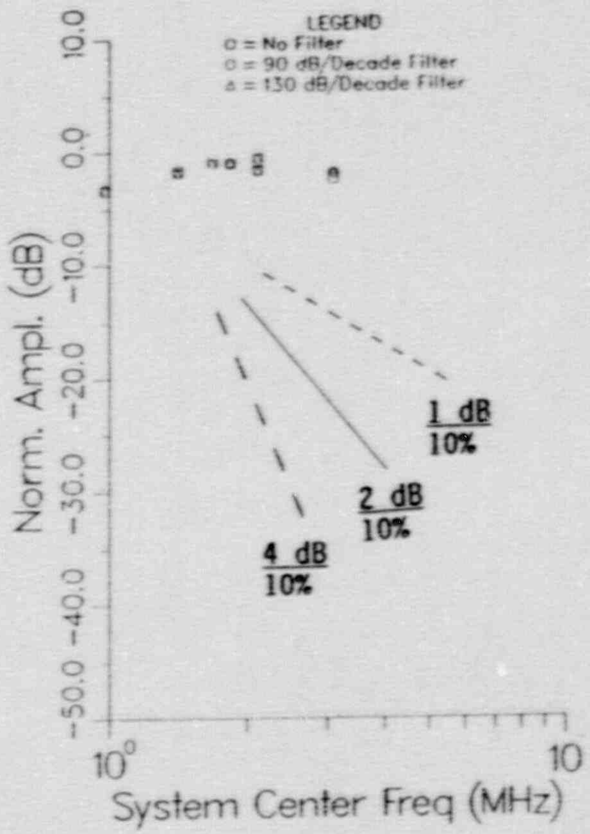

FIGURE 3.14. Center Frequency Experiment Results for the Flaw D Control Sample with and without Artificial Narrow Band Filtering

This experimental result is in agreement with the modeling result. If it is assumed that ultrasonic inspection should be repeatable to within ±2 dB (26%), the present center frequency tolerance of ±10% as given in ASME Code Case N-409-1 is not acceptable for inspection of worst-case flaws with a narrow-band UT/ISI system.

3.2.4 Future Work

The following work remains to be completed:

- Repeat this analysis for a 60° inspection angle.
- Repeat the analysis for thick sections (both 45° and 60°).
- Upgrade the flaw model to handle curved sections (nozzles) and perform equipment parameter sensitivity studies for thick sections (reactor pressure vessels) if the calculated transfer functions are worse with respect to equipment interactions than those used in the thin section studies. Consider the effects of cladding and coarse grain material.
- Develop RIL or Code recommendations, as appropriate, for equipment parameter tolerances for piping and pressure vessel inspection.
- Prepare a NUREG/CR report on pipe and pressure vessel section results.
- Publish further interaction matrix study work in peer-reviewed journals.

4.0 NEW INSPECTION CRITERIA

4.1 SUMMARY

Work continued on assessing the adequacy of existing ASME Code requirements for ISI and on developing technical bases for improving these requirements to assure safe nuclear power plant operation.

Calculations during this reporting period have applied probabilistic risk assessment (PRA) to establish inspection priorities for pressure boundary systems and components. Plant specific PRA studies have been completed for four plants (Oconee-3, Surry-1, Calvert Cliffs-1, and Crystal River-3), and four more sample plants have been selected for future evaluations. Results show a substantial range in the inspection requirements for different safety related systems within a given plant. However, the inspection priorities remain relatively constant for similar systems in different plants even for plants designed by different reactor vendors.

Development of a comprehensive probabilistic approach for improved inspection requirements continued. These efforts have focused on participation in a newly formed ASME Research Task Force on Risk-Based Inspection Guidelines.

An evaluation of data on piping service failures has been completed. The objective was to apply knowledge gained from plant operating histories as a guide for future piping inspections. The data also provided some limited insight into the successes and failures of past programs for inservice inspection. Results indicate a mixed record of success in finding defects through inservice inspection programs. While many defects have been detected during scheduled ISI, the most common method of discovering defects has been through incidental observations of leakage.

4.2 INTRODUCTION

This task is directed to the development of improved inspection requirements, with the long range goal to propose changes to ASME Section XI that will introduce the use of probabilistically-based inspection criteria. These improved criteria will help to establish priorities for selecting systems, components, and welds for inspection; and will help to determine the extent, frequency, and method of examination. The objective is to ensure that ISI programs ensure a suitably low failure probability, and thus contribute in an effective manner to the structural integrity of nuclear power plants.

In past work, we have reviewed and evaluated various concepts for probabilistic inspection criteria, and have prepared a "road map" document on improved inspection requirements. We have also been interacting with other industry efforts, notably through a newly organized ASME Research Task Force on Risk Based Inspection Guidelines. During FY88 we completed a pilot application of PRA methods to the inspection of piping, vessels, and related components. In this study, based on an existing PRA for the Oconee-3 reactor, we performed a ranking of important systems which suggested priorities for inservice inspections. In another activity, we addressed the possible use of actual failure data as a guide for inservice inspection requirements. Work continued during this reporting period with additional pilot applications of risk-based methods. These applications provide insight into the strengths and weaknesses of available methods, and provide a set of results that could form the basis for generic inspection requirements.

4.3 STATUS OF WORK PERFORMED

4.3.1 Development of Probabilistic Approaches

During this reporting period we have continued to develop alternative approaches for probabilistically-based inspection requirements. This activity is building upon concepts described in a "road map" document written during FY88.

"Road Map Document" - This document, to be published in the near future, outlines a comprehensive probabilistic approach for improved inspection requirements. The flow chart of Figure 4.1 illustrates the proposed approach which relates inspection requirements to quantitative goals for improvements in safety.

The conceptual framework of the proposed approach has been expressed in terms of three probabilistic parameters. The document reviews the computational methods and data that are now available or will be needed to put this concept into practice. Also, the assumptions and limitations of current probabilistic methods are addressed.

ASME Task Force - Activities during this reporting period have mainly consisted of participation in a newly formed ASME Research Task Force on Risk-Based Inspection Guidelines. Participation in this group has been identified as the most effective way to achieve the long range goals for improved inspection criteria.

The broad range of interests and experience represented on the ASME Task Force is expected to assist in developing practical recommendations for use of probabilistic methods that can eventually be adopted as formal ASME Section XI requirements. While the initial focus of the ASME Task Force will be on nuclear power applications, the group is also seeking insights from applications in other industries such as aircraft, petrochemical, and civil engineering structures.

The ASME Task Force is chaired by Mr. Ken Balkey of Westinghouse Electric. Dr. Brian Gore and Dr. Fred Simonen from PNL are both members of the group. The kick-off meeting was held in Chicago on November 30, 1988. All seven members of the task force were in attendance, along with six members of the steering committee that has been formed to review the work of the task force.

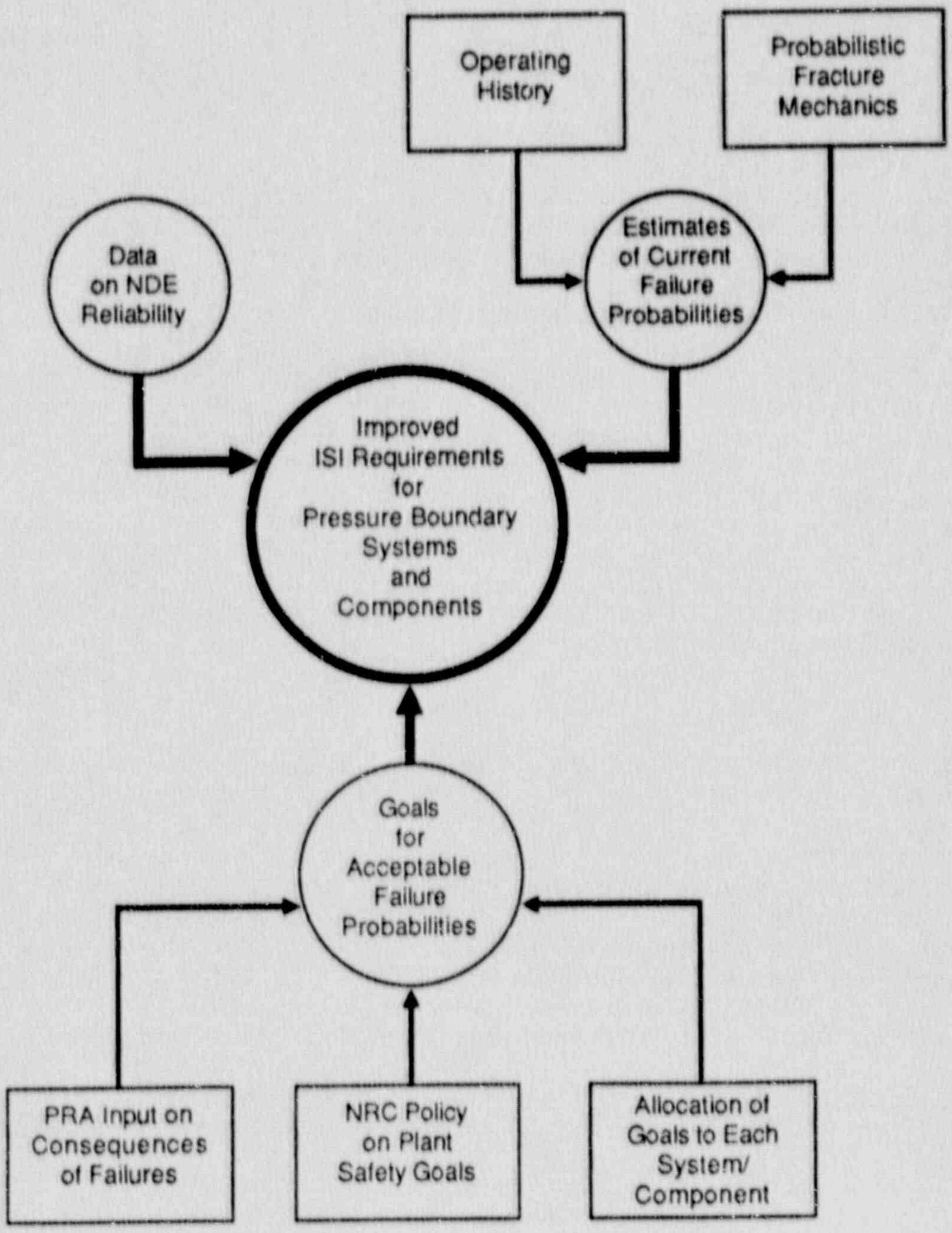

FIGURE 4.1. Probabilistic Approach to Improved ISI Requirements

The purposes of the kick-off meeting were to:

1. review the background and purpose of the project, including the work plan for Phase 1 of the research effort

2. review the current state of knowledge regarding applications of risk-based inspections.

3. define a preliminary systematic approach for risk-based inspection process

4. define action items for the next meeting.

The Task Force will meet quarterly, with the next meeting scheduled for April 11-12, 1989 in Portland, Oregon. ASME, through its Center for Research Technology and Development, is providing limited funding to help support the participation of the Task Force members.

The Phase 1 work plan calls for the Task Force to produce the following documents by December 1990:

1. A document that recommends and describes appropriate methods for establishing inspection guidelines using risk-based results for any facility or structural system.

2. A document that recommends and describes specific methods for modifying ASME Section XI to establish risk-based inspection requirements at nuclear power facilities.

4.3.2 Plant Specific PRA Applications

Work continued on a major effort that involves the application of existing Probabilistic Risk Assessments (PRA) to establish inspection priorities for pressure boundary systems and components. A pilot application of PRA methods to the Oconne-3 plant was completed during the previous year. The results of this pilot study demonstrated that PRA methods are a useful tool for identifying those systems and piping sections or welds that need to be inspected with the highest priority. During this reporting period, the scope of the Oconee-3 pilot study was expanded to address a larger sample of plants. The objective was to determine if trends from PRAs can be generalized to establish generic requirements for inservice inspection.

Selection of Plants - Table 4.1 lists the nine plants selected for evaluation during FY89. Criteria for selection of plants included:

- cross section of reactor vendors
- cross section of plant designs for each vendor
- A/E considerations
- PRA available for the plant
- exclude plants of unique and/or outdated designs

The selected plants include two each for the three PWR vendors (Westinghouse, Combustion Engineering, and Babcock and Wilcox), and two BWR plants (General Electric). The list also includes one additional Westinghouse plant. Evaluation of the Combustion Engineering Generic System 80 plant will be postponed indefinitely, since a nonproprietary PRA is not currently available. Evaluations for all of the other listed plants will be completed by the end of the next reporting period.

Results of Calculations - Evaluations were completed during this reporting period for the Surry-1, Calvert Cliffs-1, and Crystal River-3 plants. Preliminary results for these plants are described below. Another evaluation for the Peach Bottom-2 plant was nearly completed.

Tables 4.2-4.4 list the relative importance of systems based on the calculated values for the Birnbaum ranking parameter. These rankings suggest that the low pressure injection system should be given high priority for inservice inspection at all plants, and that the power conversion system should be inspected on a much lower priority basis.

The Birnbaum parameter of Tables 4.2-4.4 addresses only the consequences (core melt probability) given that a failure of the system occurs. More complete results, to be reported at a later date, will provide modified rankings that also incorporate estimated failure probabilities for each system.

Table 4.5 provides a comparison of the first four plants that have been evaluated to date. This table permits comparison of plants from three different vendors (Westinghouse, Babcock & Wilcox, and Combustion Engineering), and also a comparison of two Babcock & Wilcox plants (Oconee-3 versus Crystal River-3). Based on the results of Table 4.5, it appears that most safety systems have relatively the same rank for all the plants. In some cases, systems are designated as N/A, because the applicable PRA did not address the indicated system (i.e., either the plant does not utilize the particular system or the PRA has neglected potential failures of the system). In this regard, PRA results are currently being updated to properly address potential failure of the reactor pressure vessels.

In Table 4.5 the reactor pressure vessel, as expected, has the highest priority for inspection, since a vessel rupture has such severe safety consequences. A few of the rankings may appear surprising; for example, the number two ranking of the service water system for the Crystal River-3 plant. Also, it is notable that the low pressure injection system consistently has a higher ranking than the reactor coolant system. For the Calvert Cliffs-1 plant, the auxiliary feedwater (AFW) system was found to be unusually important. This high importance is due to the relatively frequent demands for the AFW system at this plant, and the relatively high failure probabilities associated with other failure sequences involving AFW operation.

4.3.3 Evaluation of Data from Plant Operating Histories

During this reporting period we completed an evaluation of a set of data on piping failures that was extracted from the Nuclear Power Plant Reliability System (NPRDS) data base. This evaluation was part of PNL's response to the recommendation from a 1987 workshop that past operating experience be utilized as a basis to develop improved inspection criteria. The recommendation was to search data bases and industry records for information on piping system failures and repairs, and also to review the findings of piping inspections. Specific objectives of the evaluation were:

1. Determine the completeness and usefulness of existing data on piping systems failures, and also document successes and failures of past inservice inspections.

2. Identify trends in service experience that will help guide priorities for future piping inspections.

4.3.3.1 Summary of Available Data

The evaluation began with a listing from a computerized search for all the reported piping system failures contained in the NPRDS data base. This provided some 412 individual reports of failures. It must be noted that this is a very limited and potentially biased data base. The data base gives no detail on what was inspected via ISI plan and, hence, one does not know if leaking defects had been missed by the ISI or if they were never inspected. This makes it very difficult to try to draw any conclusions about ISI effectiveness. The data reported is by purely voluntary utility participation and represents only those that wished to report data. It cannot be considered a broad or necessary representation even for the data recorded. We chose to proceed with an analysis anyway knowing that this was a severe limitation. While most of the information in the reports was not relevant to the evaluation, the narrative comments did provide some useful insight for our purpose. Each individual report was reviewed and interpreted, and then essential information was coded and entered into a computer file. A FORTRAN program was written to generate a number of useful tabulations of the coded data.

Table 4.6 highlights the most significant trends seen in the data. This tabulation addresses the methods by which the defective conditions have been discovered in the piping system. In this summary, only cases that were clearly relevant to ASME Section XI inspections were included. Only failure modes involving either cracking or wall thinning of large diameter piping were included, and only the most safety significant piping systems were addressed. Vibrational fatigue failures were also excluded from consideration, since periodic weld inspection is not considered to be the most effective and appropriate method for addressing this failure mode. In summarizing Table 4.6, the following trends are noted:

- About 50% of the defects were discovered by ultrasonic inspections performed in accordance either with ASME Section XI or on a supplementary basis. A large number of these reports corresponded to stress corrosion cracking of welds in stainless steel piping.

- Another 15% of the defects were discovered visually during code type inspections, with penetrant methods aiding in most of these detections.

- About 22% of the defects were found through incidental observations of leakage.

Utilities report information for entry into the NPRDS data base on a purely voluntary basis. Therefore, the level of completeness of reporting has been the subject of debate. Estimates of reporting (by NRC and PNL staff) have ranged from 10% to 50%. It appears that a 10% estimate would apply best to the overall fraction of data covering the entire operating history of U.S. reactors, whereas the 50% number may better reflect the notable increase in reporting seen in recent years.

A total of 72 plants have submitted at least one report for piping systems (e.g., leaks, cracks, etc.). Most of these plants have filed no more than about five reports. However, one particular plant filed a high of 67 reports. In some cases, a single report has covered several defects in a given system, while in other cases a separate report was filed for each individual defect (e.g., cracked weld). Therefore, a large number of reports for a given plant may not reflect unusually poor operating experience, but rather a thoroughness in utility reporting practice.

In spite of significant limitations, the NPRDS data base is regarded as the best available compilation of information of its type. The data base provided all the types of information that PNL was directed to compile and evaluate by the 1987 workshop recommendation. Assembly of a more complete set of data would be prohibitive in the context of the NDE Reliability Program at PNL. Such an activity would essentially require duplication and expansion of the considerable expense and efforts that have already been devoted by the nuclear power industry to assemble the NPRDS data.

4.3.3.2 Results of Detailed Tabulations

Tables 4.6-4.18 provide various tabulations of the NPRDS data relating to piping system failures. The discussion below provides brief comments on each of the tabulations. It should be emphasized that no effort was made to apply the NPRDS data to estimate failure rates for use in piping reliability evaluations. The data represent but a limited sample of plant operating experience, and few (if any) of the incident reports involved actual pipe ruptures.

Date of Discovery - (Table 4.7) - While the earliest reports date back to 1974, most of the information pertains to experience after 1980. There appears to have been a significant increase in reporting around 1984, with more than 50% of the data coming from the four years of 1984 through 1987.

Reports Per Plant - (Table 4.8) - A total of 72 plants reported at least one piping incident. A number of other operating plants (at least 10 more) either had no piping incidents, or no reports of such piping incidents were submitted to NPRDS.

Only five plants submitted more than 10 reports relating to piping. It should again be recognized that a large number of reports may not imply a poor state of piping integrity at a particular plant. Rather, it may suggest an effective plant inspection and maintenance program that finds, repairs, and reports all signs of piping degradation.

As an example, one BWR plant replaced its recirculation piping after extensive cracking of welds, and this experience was covered by only a single report to NPRDS. In contrast, another plant with a similar problem filed a report for each cracked weld. Yet another plant with extensive cracking (and replacement) of recirculation piping filed no reports at all on these problems to NPRDS. There are other cases of plants submitting a large number of individual reports for a non-structural type of problem in a secondary system (e.g., several plugged nozzles in a containment spray system).

Failure Mode Statistics - (Table 4.9) - Stress corrosion cracking was the most frequently reported mode of piping failure, involved in 26% of the incidents. Wall thinning and other modes of cracking each contributed about 19% of the remaining incidents. Vibrational fatigue (9.5%) was less frequently reported. Excluding gasket leakage, some 75% of the reported problems did involve some form of degradation to the pressure boundary, which could potentially have been detected by a program of periodic inspection.

Material Performance Trends - (Table 4.10) - Problems with austenitic (stainless) steels were reported at somewhat higher rates than for ferritic steels (56% versus 41%). However, no information was available for the relative amounts of each piping material used in actual plant construction, and therefore we can report no trends on the basis of incidents per unit length of piping run.

Discovery Method - (Tables 4.11 and 4.12) - About half of all the reported piping failures were discovered visually through incidental observations of leakage by plant personnel in the course of routine operating activities. In contrast, only 16.5% of all piping incidents were discovered by UT examination during systematic inservice inspection.

A majority of those defects discovered by UT were detected during special inspections of suspect piping (e.g., BWR recirculation lines with IGSCC), rather than during routine periodic inspections.

A high percentage of the leakage observations were for smaller diameter lines and for secondary systems. As such, the common occurrence of discovery by leakage should not necessarily be viewed as a breakdown in NDE reliability; furthermore, the leakers may not have been part of the ISI plan and were not inspected or required by ASME to be inspected.

Tables 4.6 and 4.12 list statistics on discovery method, excluding those failure incidents considered to be least relevant to Section XI inspection programs. In particular, only piping greater than 3 inches in diameter and only those failure modes addressed by periodic inspection of welds were included. Table 4.6 is further confined to the five systems of greatest safety significance. Under these restrictions, the contribution of UT type examinations (52%) becomes considerably more noteworthy.

Vendor Related Trends - (Tables 4.13-4.15) - Plants from all four of the suppliers of light water reactors were represented in the NPRDS data. In addition, there were nine reports from the Fort St. Vrain plant supplied by General Atomic.

The difference (from vendor to vendor) in the number of reports per plant was not particularly large or significant. Nevertheless, the BWR plants (6.78 reports per plant) appeared to exhibit somewhat less reliable piping performance than the average for all PWR plants (5.00 reports per plant).

System-to-System Trends - (Tables 4.16 and 4.17) - The data indicate that none of the listed systems were entirely immune from service related problems, although there was a considerable range in reports per system.

The performance of primary coolant systems in PWRs (reactor coolant system) is seen to be notably better than the comparable performance for BWR plants (reactor recirculation). This difference is even more striking when it is observed that the BWR problems include cracks in the main pressure boundary welds, whereas the PWR problems are mainly confined to small diameter fittings and branch piping.

Pipe Size Trends - (Table 4.18) - The largest number of reports were for small pipe sizes (3.0 inch diameter or smaller). Nevertheless, some 25% of the reported problems related to larger size pipes (12 inch diameter and greater). Thus there appears to be no basis to consider larger pipes less susceptible to degradation than smaller pipes.

4.4 FUTURE WORK

During the next reporting period, PRA results will be used to rank inspection priorities for four more plants (Peach Bottom-2, Zion-1, Sequoyah-1, and Grand Gulf-1). The results will be summarized in a topical report that will address general trends and the applicability of PRA methods for setting inspection priorities.

Work to develop a comprehensive approach for improved inspection requirements will move forward in coordination with the ASME Research Task Force on Risk-Based Inspection Guidelines. There will be three meetings during the next reporting period, and significant progress should be made towards the goals of the Task Force.

TABLE 4.1. Plants Selected for the Feasibility of Developing Generic Inspection Requirements

Plant Name	Vendor	PRA Source
Surry-1	Westinghouse	NUREG/CR-4550, Vol. 1
Zion-1	Westinghouse	NUREG/CR-4550, Vol. 3
Sequoyah-1	Westinghouse	NUREG/CR-4550, Vol. 5
Oconee-3*	Babcock & Wilcox	NSAC/60-SY
Crystal River-3	Babcock & Wilcox	FPC/SAI
Peach Bottom-2	General Electric	NUREG/CR-4550, Vol. 4
Grand Gulf-1	General Electric	NUREG/CR-4550, Vol. 6
Calvert Cliffs-1	Combustion Eng.	NUREG/CR-3511
Generic System** 80 PRA	Combustion Eng.	-----

* Completed (NUREG/CR-5272).

** Generic CE System 80 PRA, performed by CE vendor. Only nonproprietary information is available.

TABLE 4.2. Birnbaum Ranking for Surry System*

Rank	System	I^B
1	Low Pressure Injection (LPI)	1.6E-02
2	High Pressure Injection (HPI)	1.1E-02
3	Auxiliary Feedwater (AFW)	8.2E-03
4	Reactor Coolant (RCS)	5.9E-03
5	Charging Pump Cooling (CPC)	5.2E-03
6	Component Cooling Water	1.2E-03
7	Steam Generator (SG)	1.0E-04
8	Power Conversion (PCS)**	3.2E-06

* Only systems of interest to code-type-ISI are listed.

** Includes the main feedwater and condensate systems.

TABLE 4.3. Birnbaum Rankings for Crystal River-3 Systems*

Rank	System	I^B
1	Low-Pressure Injection (LPI)	8.4E-02
2	Service Water System (SWS)	2.1E-02
3	High-Pressure Injection (HPI)	1.3E-02
4	Reactor Coolant (RCS)	3.1E-03
5	Auxiliary Feedwater (AFW)	3.0E-03
6	Power Conversion (PCS)**	4.8E-04
7	Steam Generator (SG)	4.8E-04

* Only systems of interest to code-type-ISI are listed.

** Includes the main feedwater and condensate systems.

TABLE 4.4. Birnbaum Rankings for Calvert Cliffs-1 Plant Systems*

Rank	System	I^B
1	Auxiliary Feedwater (AFW)	2.7E-01
2	High Pressure Injection (HPI)	4.8E-02
3	Salt Water (STW)	4.5E-02
4	Service Water (SWS)	1.1E-02
5	Component Cooling Water (CCW)	1.1E-02
6	Reactor Coolant (RCS)	1.1E-03
7	Power Conversion (PCS)**	4.3E-05

* Only systems of interest to code-yype-ISI are listed.

** Includes the main feedwater and condensate systems.

TABLE 4.5. Crystal River-3, Surry-1, Oconee-3, and Calvert Cliffs-1 System Ranking Comparison

System	Birnbaum Ranking			
	CR-3	Surry-1	Oconee-3	CC-1
Reactor Pressure Vessel (RPV)	N/A	N/A	1	N/A
Low Pressure Injection (LPI)	1	1	2	N/A
High Pressure Injection (HPI)	3	2	5	2
Salt Water (STW)	N/A	N/A	N/A	3
Auxiliary Feedwater (AFW)	5	3	3	1
Reactor Coolant System (RCS)	4	4	6	6
Service Water System (SWS)	2	N/A	4	4
Charging Pump Cooling (CPC)	N/A	5	N/A	N/A
Component Cooling Water (CCW)	N/A	6	N/A	5
Power Conversion (PCS)	6	7	8	7
Steam Generator (SG)	7	8	9	N/A
Standby Shutdown Facility (SSF)	N/A	N/A	7	N/A
Instrument Air (IA)	N/A	N/A	10	N/A

TABLE 4.6. Discovery Method:

* For Wall Thinning and Cracking
* Excluding Vibrational Fatigue
* Excluding Pipe Diameters 3.0 Inch or Less
* All But Five Most Important Systems Excluded

Discovery Method	Number of Reports	
1 Ultrasonic (UT) as part of ISI program	50	(52.1%)
2 Liquid penetrant (PT) as part of ISI program	11	(11.5%)
3 Visual as part of ISI program	3	(3.1%)
4 Leakage detected as part of ISI program	9	(9.4%)
5 Leakage detected as part of some other systematic program (e.g., hydrotest, alarms, etc.)	2	(2.1%)
6 Leakage detected as incidental observation (including "walkdown types of plant inspection)	21	(21.9%)
7 Cracks detected as incidental observation	0	(0.0%)

TABLE 4.7. Date of Discovery for Incident Reports in NPRDS Data Base

Year	Number of Reports
1970	0 (.0%)
1971	0 (.0%)
1972	0 (.0%)
1973	0 (.0%)
1974	3 (.7%)
1975	7 (1.7%)
1976	18 (4.4%)
1977	18 (4.4%)
1978	8 (1.9%)
1979	9 (2.2%)
1980	33 (8.0%)
1981	7 (1.7%)
1982	18 (4.4%)
1983	40 (9.7%)
1984	75 (18.2%)
1985	75 (18.2%)
1986	62 (15.0%)
1987	32 (7.8%)
1988	7 (1.7%)
1989	0 (.0%)

TABLE 4.8. Number of Piping Failure Incident Reports Filed Per Plant

Number of Reports	Number of Plants
1- 2	27 (37.5%)
3- 5	24 (33.3%)
6-10	16 (22.2%)
11-20	2 (2.8%)
21-30	1 (1.4%)
31-40	0 (.0%)
41-50	1 (1.4%)
51-60	0 (.0%)
61-70	1 (1.4%)

TABLE 4.9. Number of Each Piping Failure Mode

	Failure Mode	Number of Reports	
1	Wall Thinning	81	(19.7%)
2	Vibration Fatigue	39	(9.5%)
3	Cracking (other than vibration fatigue or SCC, including fatigue, defective welds, "pi hole leaks", etc.)	80	(19.4%)
4	Stress Corrosion Cracking	107	(26.0%)
5	Gasket Leakage	29	(7.0%)
6	Flange Connection (Mechanical Degradation of Joint)	4	(1.0%)
7	No Degradation of Pressure Boundary (loose parts, plugged lines, failed rupture discs, etc.)	55	(13.3%)
8	Waterhammer and Other Overloads	17	(4.1%)

TABLE 4.10. Number Reported Piping Failures for Each Material Type

	Material Type	Number of Reports	
1	Austenitic Steel	229	(55.6%)
2	Ferritic Steel	168	(40.8%)
3	Rubber/Gasket/ Hose Material	9	(2.2%)
4	Other	6	(1.5%)

TABLE 4.11. Method of Discovery for the Reported Piping Failures

	Discovery Method	Number of Reports	
1	Ultrasonic (UT) as Part of ISI Program	68	(16.5%)
2	Surface Penetrant (PT) as Part of ISI Program	33	(8.0%)
3	Visual as Part of ISI Program	8	(1.9%)
4	Leakage Detected as Part of ISI Program	11	(2.7%)
5	Leakage Detected as Part of Some Other Systematic Program (e.g., hydrotest, alarms, etc.)	73	(17.7%)
6	Leakage Detected as Incidental Observation (including "walkdown types of plant inspection)	204	(49.5%)
7	Cracks Detected as Incidental Observation	15	(3.6%)

TABLE 4.12. Discovery Method:

* For Wall Thinning and Cracking
* Excluding Vibrational Fatigue
* Excluding Pipe Diameters 3.0 Inch or Less

	Discovery Method	Number of Reports	
1	Ultrasonic (UT) as part of ISI program	65	(33.0%)
2	Surface penetrant (PT) as part of ISI program	33	(16.8%)
3	Visual as part of ISI program	5	(2.5%)
4	Leakage detected as part of ISI program	9	(4.6%)
5	Leakage detected as part of some other systematic program (e.g., hydrotest, alarms, etc.)	9	(4.6%)
6	Leakage detected as incidental observation (including "walkdown types of plant inspection)	72	(36.5%)
7	Cracks detected as incidental observation	4	(2.0%)

TABLE 4.13. Number of Plants for Each Vendor

	Vendor	Number of Plants
1	Westinghouse	27 (37.5%)
2	Combustion Engineering	11 (15.3%)
3	Babcock and Wilcox	6 (8.3%)
4	General Electric	27 (37.5%)
5	General Atomic	1 (1.4%)

TABLE 4.14. Number of Reports for Each Vendor

	Vendor	Number of Reports
1	Westinghouse	136 (33.0%)
2	Combustion Engineering	61 (14.8%)
3	Babcock and Wilcox	23 (5.6%)
4	General Electric	183 (44.4%)
5	General Atomic	9 (2.2%)

TABLE 4.15. Number of Reports per Plant for Each Vendor

	Vendor	Number of Reports Per Plant
1	Westinghouse	5.05
2	Combustion Engineering	5.55
3	Babcock and Wilcox	3.83
4	General Electric	6.78
5	General Atomic	9.00

TABLE 4.16. Number of Reports Per System for All PWR Plants in Data Base

PWR System		Number of Reports	
1	Reactor Coolant System	13	(5.9%)
2	Residual (or Decay) Heat Removal System	9	(4.1%)
3	High Pressure Injection	12	(5.5%)
4	Let Down Purification and make/up and/or chemical and volume control	39	(17.7%)
5	Main Feedwater	31	(14.1%)
6	Condensate	15	(6.8%)
7	Emergency Feedwater	12	(5.5%)
8	Main Steam	2	(.9%)
9	Component Cooling Water	9	(4.1%)
10	Service Water	39	(17.7%)
11	Containment Isolation	3	(1.4%)
12	Containment Spray	30	(13.6%)
13	Reactor Building Spray	2	(.9%)
14	Reactor Building Penetration	2	(.9%)
15	Diesel Generator	2	(.9%)
16	Other	0	(.0%)

TABLE 4.17. Number of Reports Per System for All BWR Plants in Data Base

BWR System		Number of Reports	
1	Reactor Recirculation	42	(23.0%)
2	Residual Heat Removal	16	(8.7%)
3	High Pressure Injection	14	(7.7%)
4	Low Pressure Injection	20	(10.9%)
5	Feedwater	14	(7.7%)
6	Condensate	1	(.5%)
7	Steam Line/Nuclear Steam Supply Shutoff	12	(6.6%)
8	Standby Liquid Control	1	(.5%)
9	Service Water	16	(8.7%)
10	Reactor Core Isolation Cooling	3	(1.6%)
11	Isolation Condenser	29	(15.8%)
12	Containment Spray	2	(1.1%)
13	Combustion Gas Control/Dilution	1	(.5%)
14	Control Rod Drive	2	(1.1%)
15	Suppression Pool Support	3	(1.6%)
16	Diesel Generator	5	(2.7%)
17	Gas Treatment	2	(1.1%)
18	Other	0	(0.0%)

TABLE 4.18. Number of Reports Versus Pipe Diameter

Pipe Size	Number of Reports
0.0 to 3.0	151 (36.7%)
3.0 to 6.0	42 (10.2%)
6.0 to 12.0	115 (27.9%)
12.0 and greater	104 (25.2%)

5.0 PIPING TASK ACTIVITIES

This task is designed to address the NDT problems associated with the 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: mini-round robin report, qualification criteria for UT/ISI systems, piping inspection round robin report, surface roughness, field pipe characterization, and PISC-III activities.

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

- MRR Report - The Mini-Round Robin (MRR) subtask was conducted to provide an engineering data base for UT/ISI that would help: a) quantify the effect of training and performance demonstration testing that resulted from IEB 83-02, b) quantify the differences in capability between detecting long versus short cracks, and c) quantify the capability of UT/ISI technicians to determine length and depth of intergranular stress corrosion cracks (IGSCC). The report, prepared to document the work conducted under this subtask, is being revised to accommodate NRC review comments.

- Qualification Criteria for UT/ISI Systems - The objective of this subtask is to improve the reliability of UT/ISI through the development of new criteria and requirements for qualifying UT/ISI systems. The qualification document (NUREG/CR-4882) was submitted for NRC review during the last reporting period and work on this subtask was minimal pending receipt of the NRC comments.

- Surface Roughness Conditions - The objective of this subtask is 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. Past efforts included an attempt to quantify the effect produced by irregularities of the inspection surface. This subtask was then rescoped as a cooperative effort with the Center for NDE (under EPRI funding) to establish a mathematical model to be used as an engineering tool for deriving guidelines for surface specifications. The primary activity during this reporting period was to define a set of field problems that involve various surface conditions, transducer configurations, and flaw types. This action satisfied Milestone 1.a. and PNL Responsibility 4 of the "Integration and Coordination Plan for EPRI and NRC NDE Programs to Assess and Develop Specifications for Surface Finish."

- 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. A specimen set has been prepared for shipment to Europe for use in PISC-III program studies; however, actual shipment has been deferred pending resolution of a problem on the ability of the JRC in Ispra, Italy to handle highly contaminated specimens.

- 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); providing five safe-ends from the Monticello plant; providing a sector of the Hope Creek reactor pressure vessel containing two recirculation system inlet nozzles; coordination of the inspections to be conducted by U.S. teams on the various actions; input to the studies on reliability and specimens for use in the parametric, capability, and reliability studies of the AST. Planning continued on the specimens for the AST with all the wrought stainless steel specimens for the capability studies being identified. U.S. companies were contacted to coordinate the inspections to be performed by them on the three dissimilar metal weld PISC-III samples that were to come to the U.S. between April and September 1989.

5.1 MINI-ROUND ROBIN REPORT

5.1.1 Introduction

The Mini-Round Robin (MRR) subtask was conducted to provide an engineering data base for UT/ISI that would help:

- quantify the effect of training and performance demonstration testing that resulted from IEB 83-02,

- quantify the differences in capability between detecting long (greater than 3-in.) cracks versus short (less than 2-in.) cracks, and

- quantify the capability of UT/ISI technicians to determine length and depth of intergranular stress corrosion cracks (IGSCC).

5.1.2 Status of Work Performed

A NUREG/CR was prepared to document the work conducted under this subtask, and this report was submitted for NRC review. Comments from the NRC review were received and work is in progress to accomplish the extensive revisions necessary to address technical issues and accommodate review comments. A paper entitled "An Evaluation of Ultrasonic Inspection for Intergranular Stress Corrosion Cracks Through Round-Robin Testing" was accepted for publication in Materials Evaluation (Taylor et al. 1989).

5.1.3 Future Work

After all review comments have been incorporated, and various other editorial and technical changes have been made, the NUREG/CR report will be resubmitted for NRC review and publication.

5.2 QUALIFICATION CRITERIA FOR UT/ISI SYSTEMS

5.2.1 Objective

The objective of this subtask is to improve the reliability of ultrasonic testing/inservice inspection (UT/ISI) through the development of new criteria and requirements for qualifying UT/ISI systems. Revisions to the qualification document (NUREG/CR-4882) to resolve technical issues and address review comments is in progress. This document has received PNL clearance, been submitted to the NRC for review, and additional NRC comments have been received.

5.2.2 Status of Work Performed

Development of criteria and requirements for qualifying UT/ISI systems continued with additional editing of the qualification document (NUREG/CR-4882, entitled "Qualification Process for Ultrasonic Testing on Nuclear Inservice Inspection Applications") as a formal report. Technical issues have been identified and addressed, and the document was revised and submitted to NRC for pre-publication review. Additional NRC comments were received, and the document is undergoing additional revision to accommodate these later comments.

5.2.3 Future Work

Comments received from the NRC during this reporting period resulted in the need for additional revisions to this document. When completed, the document will be submitted for final NRC pre-publication review. Upon receipt of NRC concurrence, NUREG/CR-4882 will be submitted for publication by the NRC. When published, this document will describe recommended qualification processes for all nondestructive examination/inservice inspection (NDE/ISI) systems, although the document primarily addresses criteria and qualification processes for UT/ISI systems.

5.3 SURFACE ROUGHNESS CONDITIONS

5.3.1 Introduction

The objective of this subtask is to establish specifications such that an effective and reliable ultrasonic inspection is not precluded by the condition of the inspection surface. Past efforts included an attempt to quantify the effect produced by inspection surface irregularities. This subtask was then rescoped as a cooperative effort with EPRI to establish a mathematical model to be used as an engineering tool for deriving guidelines for surface specifications.

5.3.2 Status of Work Performed

Previous activities included formulation of a coordination plan between EPRI, NRC, the Center for NDE (CNDE) at Ames Laboratory, and PNL; development of better PNL experimental procedures for obtaining quantitative data for comparison with the model predictions; an exchange of data between CNDE and

PNL; and comparing the CNDE ultrasonic model with PNL experimental data. Activities for this reporting period included formulation of a matrix that outlines field cases of interest for the CNDE model and preparation of a paper for Materials Evaluation.

Determining the "Inspection-Flaw-Material-Transducer Matrix for CNDE Model" was significant because it completed Milestone 1.A. and PNL Responsibility 4 of the EPRI/NRC coordination plan. This matrix (see Appendix A) listed specific surface conditions together with material types, flaw types, and typical transducers used in the field. We specified these conditions to CNDE at the beginning of the program, communicated to CNDE how the model will be used when transferred to PNL and that the model was expected to address all of these field situations. The milestone and PNL responsibility as given in the EPRI/NRC coordination plan are as follows:

> Milestone 1.A.. Collaboration between CNDE and PNL to review Phase II work to ensure the experimental data collected by PNL and the theoretical data generated by the CNDE are in unison for basic model validation.
>
> PNL Responsibility 4. PNL will define typical ISI parameters for contact testing of piping-type applications. These applications will be separated into cases for clad ferritic steel, wrought stainless steel, and cast stainless steel.

Through the efforts of experimentally measuring an ultrasonic field and quantifying field parameters for refining the CNDE model, sufficient technical data has been developed to draft an article for submission to a journal such as Materials Evaluation. This article will document usage of a longitudinal-wave microprobe to acquire ultrasonic field maps and demonstrate various applications by mapping fields produced by longitudinal-wave and shear-wave search units.

5.3.3 Future Work

About one and one-half years of this planned three-year effort has now been completed. During the next year, this subtask will continue to involve collection of experimental data for both development and evaluation of the CNDE model. Upon model validation, PNL will acquire the mathematical model (planned for March 1990) and use the model during the third year as an engineering tool to derive guidelines for surface specifications. PNL will continue to refine experimental procedures for qualitatively measuring an ultrasonic field.

5.4 CHARACTERIZATION OF FIELD PIPE

5.5.1 Introduction

The objective of this subtask is to provide pipe weld specimens that can be used to help determine the effectiveness and reliability of ultrasonic inservice inspection (UT/ISI) that is performed on BWR piping. This goal will be accomplished by supporting PNL laboratory studies and providing specimens that will be used in other work such as PISC III.

5.4.2 Status of Work Performed

Weld specimens removed from replaced pipe remnants from the Monticello and Vermont Yankee BWR nuclear power plants became available during FY 1986. Due to high amounts of alpha contamination on the Monticello specimens, it was decided to decontaminate only the 11 Vermont Yankee specimens and wait until FY87 to have the 28 Monticello weld specimens decontaminated. A complete characterization was performed by PNL personnel on the 11 Vermont Yankee weld specimens; this included ultrasonic and penetrant examinations. The 28 Monticello weld specimens were decontaminated by an off-site contractor in FY87. Upon completion of the decontamination, PNL personnel performed weld profile measurements and penetrant examinations on all Monticello weld specimens. Some of these weld specimens were then manually UT and SAFT scanned to help select a specimen matrix for the PISC-III exercise. These data were thoroughly analyzed and a test matrix was selected for PISC-III.

5.4.3 Future Work

The work under this task is complete and we are now awaiting the final selection of weld specimens for the PISC-III program to place the remaining specimens in storage.

5.5 PISC-III ACTIVITIES

5.5.1 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.

5.5.2 Status of Work Performed

The RCS work is being followed and efforts have been expended to provide some safe-ends removed from the Monticello plant for this Action. These safe-ends became available when the recirculation system was replaced. These safe-ends are radioactive, and most of them have contact readings on their storage cylinders in excess of 1R at the hottest place. Five safe-ends are being considered of which two have weld overlays and three do not. One of the weld overlays had reported a through-wall crack during the weld overlay process. Problems have been encountered because the safe-ends have high alpha contamination, and the hot cells at Ispra were set up for gamma shielding and were not designed to handle high alpha contamination. This activity is still on hold until the alpha contamination issue can be resolved.

Participation in the NDW has been in the form of aiding the coordination of the samples that will be coming to the U.S. in 1989. This involves contacting the inspection groups and ensuring arrangements and schedules will be met during the slotted inspection time. Extensive planning was made with potential USA companies for inspecting the three dissimilar metal welds that will be arriving in the U.S. between April and August 1989. To date, two companies have committed to inspect the three specimens. Hopefully, others will join in participation of this action.

Since PNL staff are major contributors to design, implementation, and analysis of studies in the AST, additional planning on the acquisition of materials and defects has taken place. The PISC-III program will purchase the needed CCSS material for the capability, parametric, and reliability studies on these coarse grained materials. During a meeting of the AST in December 1988, the attendees wanted to have more emphasis on the real defects and wanted to include any appropriate European specimens. Once information is received on the welds removed from the Muhlenberg plant in Switzerland, the design will be finalized for the wrought stainless steel reliability study. All the material exists for the capability study on the wrought material except for two thermal fatigue cracks. A specimen will be sent from Italy for PNL to use in introducing these cracks for the PISC-III program.

Participation has occurred in the PISC-III Managing Board meetings to follow and advise on issues as they develop.

5.5.3 Future Work

Time will be spent in the coordination of the three dissimilar metal welds that will be arriving during the next six-month period. Finalization of the AST design for the reliability studies will occur and two thermal fatigue cracks will be placed in a wrought stainless steel specimens sent from Italy. The final call for participation should be going out at the end of the next reporting period.

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APPENDIX A

Matrix of Surface Conditions and

Ultrasonic Inspection Parameters for

EPRI/NDE Study

by

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Matrix of Surface Conditions and

Ultrasonic Inspection Parameters for

EPRI/NRC Study

An approved coordination plan between EPRI and the NRC calls for the Center for NDE (CNDE) at Ames Laboratory to refine an already existing model of ultrasonic-wave phenomena such that it may be used as an engineering tool to determine surface condition specifications. (This work at the CNDE is sponsored by EPRI.) The plan also calls for the Pacific Northwest Laboratory (PNL) under NRC sponsorship to obtain experimental measurements for CNDE and to evaluate the model. To guide model refinement, a matrix of surface conditions and ultrasonic inspection parameters were defined that the model should be able to replicate at the completion of the coordination plan. The matrix focused on the following 10 surface conditions: diametrical shrink, excessive weld crown, weld splatter, over-ground condition, weld overlay, pressurized water reactor (PWR) vessels, boiling water reactor (BWR) vessels, nozzles, and bi-metallic and tri-metallic welds. Each surface condition is defined and subdivided into diversity of surface geometry; material; samples; and combinations of flaws, materials, and probes. The purpose of the matrix is to indicate various runs that PNL will attempt when a copy of the software is transferred to PNL.

DIAMETRICAL SHRINK

The circumferential weld has a smaller diameter than the pipe and deforms the original pipe material (Figure 1). The radius of curvature is formed by shrinkage of weld metal during welding.

1. Surface geometry diversity - Condition is most severe for thin-walled pipe with large diameters. Significant diametrical shrink occur for BWRs in 4- and 6-inch Schedule 80 piping (9-mm wall thickness) such as the control rod device (CRD) line and the reactor water clean up (RWCU) line. In PWRs, 6- and 18-inch piping with wall thickness between 3 and 10 mm occur for the safety injection line.

2. Material type is carbon steel and wrought stainless steel piping since diametrical shrinkage is only significant with thin-walled piping.

3. Samples: 10-inch Schedule 80 pipe section - 0.072" shrinkage
   14-inch Schedule 40 pipe section - 0.077" shrinkage
   24-inch Schedule 100 pipe section - 0.106" shrinkage

4. Combinations of Flaw, Material, and Transducers

   A. Combination 1

      1. Flaw - circumferential crack (nearly radial in orientation)
      2. Material - carbon steel
      3. Transducers

a. < 15 cm dia. - SV[a], 2 MHz, 6 mm dia., 45°, 1 E[b]
b. 15 < 25 cm d.- SV, 2 MHz, 6-13 mm dia., 45 & 60°, 1 E
c. 25 < 50 cm d.- SV, 2 MHz, 13-25 mm dia., 45 & 60°, 1 E
d. ≥ 50 cm dia. - SV, 1-2 MHz, 13-25 mm dia., 45 & 60°, 1 E

B. Combination 2

1. Flaw - circumferential crack (nearly radial in orientation)
2. Material - wrought stainless steel
3. Transducers (Dual element probes may be used instead of single element probes when pipe wall thickness ≥ 19 mm)

a. < 15 cm dia. - SV, 2 MHz, 6 mm dia., 45°, 1 E
b. 15 < 25 cm d.- SV, 1.5-2 MHz, 6-13 mm dia., 45 & 60°, 1 or 2 E
c. 25 < 50 cm d.- SV, 1.5-2 MHz, 10-25 mm dia., 45 & 60°, 1 or 2 E
d. ≥ 50 cm dia. - SV, 1.0-2 MHz, 13-25 mm dia., 45 & 60°, 1 or 2 E
e. SLIC-40[c] used for sizing [Manufacturers - Southwest Research Institute (SwRI), Universal Testing Labs, and Combustion Engineering (CE)]
f. 30-70-70 used for sizing [Not much credit is given to this technique since ID and OD surfaces are typically not parallel to counter bores. Therefore, the technique is used almost solely as a confirmation technique. (No signal < 10% through-wall depth (TWD); observable signal infers a 10 to 50% TWD; saturated signal ≥ 50% TWD)]. (Probe Manufacturer - Krautkramer)

EXCESSIVE WELD CROWN

Excessive weld material usually protrudes above one or more of the adjoining surfaces being welded together and is commonly called weld reinforcement (Figure 2). Weld reinforcement may be in the as-welded, partially ground, or blended ground state. Usually a step-like protrusion exists from a partially ground condition. Weld material may extend excessively beyond the typical bounds of a weld if weld repair was performed or if weld material is used to blend the height

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(a) Wave-mode designations shall be SV and L for vertically polarized shear waves and longitudinal waves, respectively.

(b) The abbreviated form "1 E" and "2 E" correspond, respectively, to single and dual element probes. Dual element probes have refracted, skew, and rotational angles and a given distance between the two crystals. Thus, the surface condition pertinent to the transmitter may be significantly different than that affecting the receiver and the added construction angles may affect the degree that surface condition affects the interaction between field envelopes.

(c) SLIC-40 is a probe designation developed by George Gruber of Southwest Research Institute (SwRI). The SLIC-40 uses shear and longitudinal waves for inspection and characterization. The number 40 is the average of the shear and longitudinal refracted angles.

difference between two components. [Step discontinuities are very common in the field. A good inspector will require surface preparation. Very often the inspector will remove a portion of the wedge front to gain access to the area of interest. A 60° SV probe is NOT as useful as those of 50° and less since it does not produce a strong corner reflector. A general rule of thumb is to use angles ≤ 55°. Some inspectors may be inclined to use a 3/2-V path to circumvent the problem. A 3/2-V path, however, is NOT beneficial since the step discontinuity still affects the field at the 1-V point (see Figure 2).]

1. Surface Step Discontinuity - As-welded and partially grounded welds are considered since they may cause the probe to tilt (resulting in an altered refracted angle) and permit reverberation between probe wedge and component.

2. Material types are carbon steel, austenitic stainless steel, and cast stainless steel.

3. Samples: No specific samples are given; however, an array of welded samples of all material types is present at the Pacific Northwest Laboratory.

4. Combinations of Flaw, Material, and Transducers

   A. Combination 1

      1. Flaw - circumferential crack (nearly radial in orientation)
      2. Material - carbon steel
      3. Transducers

         a. ≤ 25 cm dia. - SV, 2 MHz, 6-13 mm dia., 45 & 60°, 1 E
         b. 25 ≤ 50 cm dia.- SV, 2 MHz, 13-25 mm dia., 45 & 60°, 1 E
         c. ≥ 50 cm dia. - SV, 1-2 MHz, 13-25 mm dia., 45 & 60°, 1 E

   B. Combination 2

      1. Flaw - circumferential crack (nearly radial in orientation)
      2. Material - wrought stainless steel
      3. Transducers (Dual element probes may be used instead of single element probes when pipe wall thickness ≥ 19 mm)

         a. ≤ 25 cm dia. - SV, 1.5-2 MHz, 6-13 mm dia., 45 & 60°, 1 or 2 E
         b. 25 ≤ 50 cm d.- SV, 1.5-2 MHz, 10-25 mm dia., 45 & 60°, 1 or 2 E
         c. ≥ 50 cm dia. - SV, 1.0-2 MHz, 13-25 mm dia., 45 & 60°, 1 or 2 E
         e. SLIC-40 used for sizing.
         f. 30-70-70 used as a confirmation sizing technique.

   C. Combination 3

      1. Flaw - circumferential crack (nearly radial in orientation)
      2. Material - cast stainless steel
      3. Transducers

a. L, 1.0 MHz, 25 x 25 mm crystals, 40°, 2 E, 47 x 79 mm[a]
b. L, 1.0 MHz, 20 x 15 mm crystals, 45°, 2 E, 36 x 47 mm

WELD SPLATTER

Discrete points at which welding material has splattered to and adhered to the pipe (Figure 3). Weld splatter typically is in the form of a half sphere and, thus, enables the transducer to rotate and rock about a point and cause the refracted angle to sweep through a fixed range and a lateral misdirection of the field. A distribution of weld splatter may also lift the transducer off the surface.

1. Surface Geometry Diversity - Samples at PNL were examined for weld splatter. When weld splatter was observed, height and diameter measurements were made.

   a. 0.049" high and 0.111" dia.
   b. 0.041" high and 0.076" dia.
   c. 0.030" high and 0.069" dia.
   d. 0.020" high and 0.038" dia.
   e. 0.015" high and 0.021" dia.

2. Material types are carbon steel, austenitic stainless steel, and cast stainless steel.

3. Available samples: A 25.4-cm Schedule 80 pipe of wrought stainless steel having weld splatter as listed in item 1.

4. Combinations of Flaw, Material, and Transducers

   A. Combination 1

      1. Flaw - circumferential crack (nearly radial in orientation)
      2. Material - carbon steel
      3. Transducers

         a. $\leq$ 25 cm dia. - SV, 2 MHz, 6-13 mm dia., 45 & 60°, 1 E
         b. 25 $\leq$ 50 cm dia.- SV, 2 MHz, 13-25 mm dia., 45 & 60°, 1 E
         c. $\geq$ 50 cm dia. - SV, 1-2 MHz, 13-25 mm dia., 45 & 60°, 1 E

   B. Combination 2

      1. Flaw - circumferential crack (nearly radial in orientation)
      2. Material - wrought stainless steel
      3. Transducers

(a) Rectangular dimensions of the transducer contact surface are respectively given in the plane of ultrasonic incidence and normal to that.

a. $\leq$ 25 cm dia. - SV, 1.5-2 MHz, 6-13 mm dia., 45 & 60°, 1 or 2 E
b. 25 $\leq$ 50 cm d.- SV, 1.5-2 MHz, 10-25 mm dia., 45 & 60°, 1 or 2 E
c. $\geq$ 50 cm dia. - SV, 1.0-2 MHz, 13-25 mm dia., 45 & 60°, 1 or 2 E
e. SLIC-40 used for sizing
f. 30-70-70 used as a confirmation sizing technique.

C. Combination 3

1. Flaw - circumferential crack (nearly radial in orientation)
2. Material - cast stainless steel
3. Transducers

a. L, 1.0 MHz, 25 x 25 mm crystals, 40°, 2 E, 47 x 79 mm
b. L, 1.0 MHz, 20 x 15 mm crystals, 45°, 2 E, 36 x 47 mm

OVER-GROUND CONDITION

By blending weld reinforcement into the pipe, a concave surface may be formed and is frequently referred to as over-ground (Figure 4). The grinding operation typically makes a wavy surface along the pipe circumference. When a probe is applied to the surface, either a gap may exist under the probe or a convex surface may exist on which the probe may rock or pivot. This same condition may also be found on large components where a repair was performed which involved grinding away a large amount of material. (A vessel or pump bowl may have several cm of material removed in a localized area and still satisfy Code requirements.)

1. Surface Geometry Diversity - Two cases may be considered; one with relatively large diameter pipe which is one dimensional, and the second with small diameter pipe where the curvature of the outer diameter surface and the over ground must be considered collectively. The amount of maximum over ground may be proportional to the as-welded weld reinforcement and pipe thickness. Over grounds of approximately 6 mm may exist.

2. Material types are carbon steel, austenitic stainless steel, and cast stainless steel.

3. Available samples: No specific samples given; however, an array of welded samples of all material types is present at the Pacific Northwest Laboratory.

4. Combinations of Flaw, Material, and Transducers

A. Combination 1

1. Flaw - circumferential crack (nearly radial in orientation)
2. Material - carbon steel - large and small diameter piping
3. Transducers

a. $\leq$ 25 cm dia. - SV, 2 MHz, 6-13 mm dia., 45 & 60°, 1 E
b. 25 $\leq$ 50 cm dia.- SV, 2 MHz, 13-25 mm dia., 45 & 60°, 1 E
c. $\geq$ 50 cm dia. - SV, 1-2 MHz, 13-25 mm dia., 45 & 60°, 1 E

B. Combination 2

1. Flaw - circumferential crack (nearly radial in orientation)
2. Material - wrought stainless steel - large and small diameter piping
3. Transducers

   a. ≤ 25 cm dia. - SV, 1.5-2 MHz, 6-13 mm dia., 45 & 60°, 1 or 2 E
   b. 25 ≤ 50 cm d.- SV, 1.5-2 MHz, 10-25 mm dia., 45 & 60°, 1 or 2 E
   c. ≥ 50 cm dia. - SV, 1.0-2 MHz, 13-25 mm dia., 45 & 60°, 1 or 2 E

C. Combination 3

1. Circumferential crack (nearly radial in orientation)
2. Cast stainless steel - large diameter piping
3. Transducers

   a. L, 1.0 MHz, 25 x 25 mm crystals, 40°, 2 E, 47 x 79 mm
   b. L, 1.0 MHz, 20 x 15 mm crystals, 45°, 2 E, 36 x 47 mm

WELD OVERLAY

Weld overlay repaired pipe joints are characteristic of a complex geometry and several flaw types (Figure 5). The surface is cladded and potential flaws include a deep planar crack that may extend into the weld overlay material, lack of fusion in the weld overlay material, cracking in the weld overlay material, and lack of bond between weld overlay material and original pipe material. The cladded surface is typically ground and may leave shallow but narrow and steep troughs in the cladded surface.

1. Surface Geometry Diversity - Various degrees of grinding may be performed on the as-welded surface; e.g., 50, 80, 90, and 100%. The surface will also have superimposed on it a hand-ground surface (wavy with two-dimensional curves and step discontinuities).

2. Material types are austenitic cladding on wrought stainless steel pipe joints.

3. Available samples - A weld overlaid pipe exists at PNL. Weld overlay is a weld repair method and in the field always has a weld under the overlay material. (The sample at PNL, however, does not have a weld underneath it.)

4. Combinations of Flaw, Material, and Transducers

   A. Combination 1

   1. Flaw - large planar crack (circumferential) originating from original pipe material
   2. Material - weld overlay and original pipe material

3. Transducers

   a. RTD 82-507 - L, 4 MHz, 20 x 20 mm, 45°, FL=20 mm, 2 E (RTD stands for Rontgen Technische Dienst (RTD) of Rotterdam, Netherlands)
   b. RTD 83-988 - L, 2 MHz, 26 x 26 mm, 60°, FL=30 mm, 2 E
   c. RTD 82-517 - L, 2 MHz, 26 x 26 mm, 70°, FL=17 mm, 2 E

B. Combination 2

1. Flaw - large planar cracks extending into overlay material, small overlay cracks, and lack of fusion
2. Material - weld overlay material
3. Transducers

   a. RTD 82-518 - L, 2 MHz, 20 x 20 mm, 70°, FL=15 mm, 2 E
   b. RTD 82-516 - L, 2 MHz, 37 x 37 mm, 70°, FL=18 mm, 2 E
   c. Automation - SV, 2 MHz, 13 mm dia., 45°, 1 E

C. Combination 3

1. Flaw - lack of bond
2. Material - weld overlay material
3. Transducer

   a. RTD 82-511 - L, 2 MHz, 0°, FL=20 mm, 2 E

PWR VESSELS

PWR vessels are typically inspected from within which requires the ultrasonic field to pass through cladding to access regions where surface, subsurface, laminar, and linear flaws may be located (Figure 6). Vessel wall thickness typically run between 8 and 12 inches.

1. Surface Geometry Diversity - Numerous cladding schemes exist for pressure vessels (Figure 7) and typically include automated strip clad with manual welding usually found about the vessel welds. Surface grinding may vary significantly from case-to-case. (Single-wire produces a 1/2-inch wide strip and 2- and 3-wire strip produce a 1.5- to 2-inch wide strip. Field experience suggests that the 2- and 3-wire strip produces a much better scanning surface.) Other surface geometries are illustrated in Figures 8 through 10. Repairs can also result in large grinding gouges elliptical in shape and 6 mm in depth.

2. Material type is carbon steel cladded by austenitic stainless steel.

3. Available samples include five 60 x 60 x 9 cm blocks of strip clad of different widths and manually applied wire clad. All samples are in the as-welded state except one that was ground flat.

4. Combinations of Flaw, Material, and Transducers - [Scanning is usually implemented in the contact mode with probe wedges independently gimbaled. Some immersion scanning is performed with the front surface signal used to electronically trigger the metal path. (A typical water path is 8 cm.) Immersion scanning with sleds for surface following is usually not performed. B&W uses immersion, SwRI uses contact, and Westinghouse uses immersion and contact. (The vast majority of probes used on vessels are 2 MHz.)]

A. Combination 1

1. Flaw - surface (normal) cracks (cladded ID or OD) - if cladded surface, do not include clad thickness in measurement of "a."

   a. t = 8", a = 0.15", and l = infinity or 360° around [(a)]
   b. t = 8", a = 0.42", and l = 0.83"
   c. t = 12", a = 0.23", and l = 360°
   d. t = 12", a = 0.62", and l = 1.24"

2. Material - cladded near surface or uncladded far surface

3. Transducers (Others to be added via survey of inspectors)

   a. L, 2 MHz, 38 mm dia., 0°, 1 E (used to detect laminar flaws and to implement delta technique with 45°, SV probes)
   b. L, 5 MHz, 13 x 25 mm, 0°, 1 E (used to implement high resolution scans for sizing)
   c. SV, 2 MHz, 38 mm dia., 45°, 1 E (pitch/catch mode with one skip distance between probes. This is usually not implemented.)
   d. SV, 2 MHz, 38 mm dia., 60°, 1 E
   e. RTD - L, 2 MHz, 75 x 75 mm, 70°, 2 E
   f. L, 1 MHz, F. Depth 226 mm, 6 dB widths 12 x 11 mm, 0° (an Intercontrole transducer[(b)], probably model 1-L-130-10 with crystal diameter 130 mm and 100 mm water depth and 226 mm steel depth)
   g. SV, 1 MHz, F. Depth 216 mm, 6 dB widths 9 x 10 mm, 45° (an Intercontrole transducer, probably model 1-T-130-8 with crystal diameter 130 mm and 100 mm water depth and 226 steel depth)
   h. SV, 1 MHz, F. Depth 219 mm, 6 dB widths 16 x 14 mm, 60° (an Intercontrole transducer, model number unknown, 219 mm steel depth)

(a) ASME code defines "t" as wall thickness, "a" as flaw width, and "l" as flaw length.

(b) Intercontrole of France is a transducer manufacturer which specializes in immersion transducers. The transducers have compound curvature lenses to minimize the effects of aberrations due to the curvature of the inside diameter surface and to achieve the proper focusing at the selected depth in the vessel wall.

i. L, 2 MHz, F. Depth 226 mm, 6 dB widths 11 x 9 mm, 45° (an Intercontrole transducer, model number unknown, 226 steel depth)

B. Combination 2 - Subsurface (normal) cracks contained within vessel wall (Do NOT use since outer and inner diameter flaws are more restrictive.)

C. Combination 3

1. Laminar flaws (AREA = 0.75 x L x W where L = DETECTED LENGTH and W = DETECTED WIDTH, according to Sec. XI IWA-3360 of ASME Code)

   a. t = 8" then w x l =24 sq. in., using a 4:1 ratio for width to length, a 2.5" x 9.8" is determined.
   b. t = 12" then w x l =36 sq. in., using a 4:1 ratio, a 3.0" x 12.0" is determined.

2) Material - cladded near surface or uncladded far surface

3) Transducers - same as reported in 4.A.3.a., 4.A.3.b., 4.A.3.c., 4.A.3.f, and possibly others.

D. Combination 4 - linear flaws - Already included in Combination 1 since ASME Code Table IWB-3510-3 refers back to Table IWB-3510-1 when UT is able to define "a" and "l".

BWR VESSELS

BWR vessels are typically inspected from the outside; however, scale and paint flaking often prevent adequate acoustic coupling and result in a limited examination. Vessel wall thickness typically runs between 8 and 12 inches.

1. Surface Geometry Diversity - Defined in BWR vessel description.

2. Material type is carbon steel.

3. Available samples - Potential samples may be the large vessel portions acquired from Hope Creek or large blocks of carbon steel.

4. Combinations of Flaw, Material, and Transducers (same as used for PWR)

   A. Combination 1

   1) Flaw - surface (normal) cracks (cladded ID or OD) - if cladded surface, do not include clad thickness in determination of flaw size.

      a. t = 8" then a = 0.15" l = 360° or a = 0.42" l = 0.83"
      b. t = 12" then a = 0.23" l = 360° or a = 0.62" l = 1.24"

   2) Material - uncladded near surface and cladded far surface

3) Transducers (Others to be added via survey of inspectors)

a. L, 2 MHz, 38 mm dia., 0°, 1 E (used to detect laminar flaws and to implement delta technique with 45°, SV probes
b. SV, 2 MHz, 38 mm dia., 45°, 1 E (two transducers used - pitch/catch mode with one skip distance apart)
c. SV, 2 MHz, 38 mm dia., 45°, 1 E (two transducers used - pitch/catch mode with one skip distance apart)
d. L, 5 MHz, 13 x 25 mm, 0°, 1 E (used to implement high resolution scans for sizing)
e. Intercontrole transducers are not considered since they require immersion techniques for achieving focusing

B. Combination 2 - Subsurface (normal) cracks contained within vessel wall (Do NOT use since outer and inner diameter flaws are more restrictive.)

C. Combination 3

1) Laminar flaws

a. t = 8", a x l =24 sq. in., using a 4:1 ratio. a 2.5" x 9.8" flaw is determined.
b. t = 12", a x l =36 sq. in., using a 4:1 ratio, a 3.0" x 12.0" flaw is determined.

2) Material - carbon steel

3) Transducers - same as reported in 4.A.3)a., 4.A.3)b., and possibly others.

D. Combination 4 - Linear flaws - Already included in Combination 1 since ASME Code Table IWB-3510-3 refers back to Table IWB-3510-1 when UT is able to define "a" and "l".

<u>NOZZLES</u>

Four different nozzle designs are given in ASME Code; i.e., barrel, flange, set-on, and integrally cast (Figures 11-14). A major source of difficulty is the compound curvature produced by that of the vessel curvature and that of the nozzle. [The flange design is widely used and, depending on flange length, may provide access to the nozzle-vessel weld for a 45°, SV-wave probe. Contact or immersion scanning may be performed. This is usually accomplished by taking the mechanical fixture that is centered on the vessel flange and telescoping a centering fixture into the nozzle. A contact or immersion probe is used to access the nozzle-vessel weld with a L-wave probe with a refracted angle so that the ray path would be perpendicular to a planar crack, if present. A 45° SV probe pointed back toward the vessel may also be used. Creeping wave probes are typically not used on the nozzle inside corner region. SwRI uses an incident angle to set up a surface wave. The rough cladding produces spurious signals; however, a flaw signal is reported to generally be much stronger.]

Possible specimens include those to be used in the PISC IV program. (PISC is an international program for the inspection of steel components.)

BI-METALLIC AND TRI-METALLIC WELDS

These welds join the nozzle and piping and are generally accessible from the piping side only. This requires far-side inspection of the nozzle root area which means wave propagation through the complex weld structure. At this time, I recommend using the same transducers as used on CCSS.

Possible specimens include those to be used in the PISC IV program.

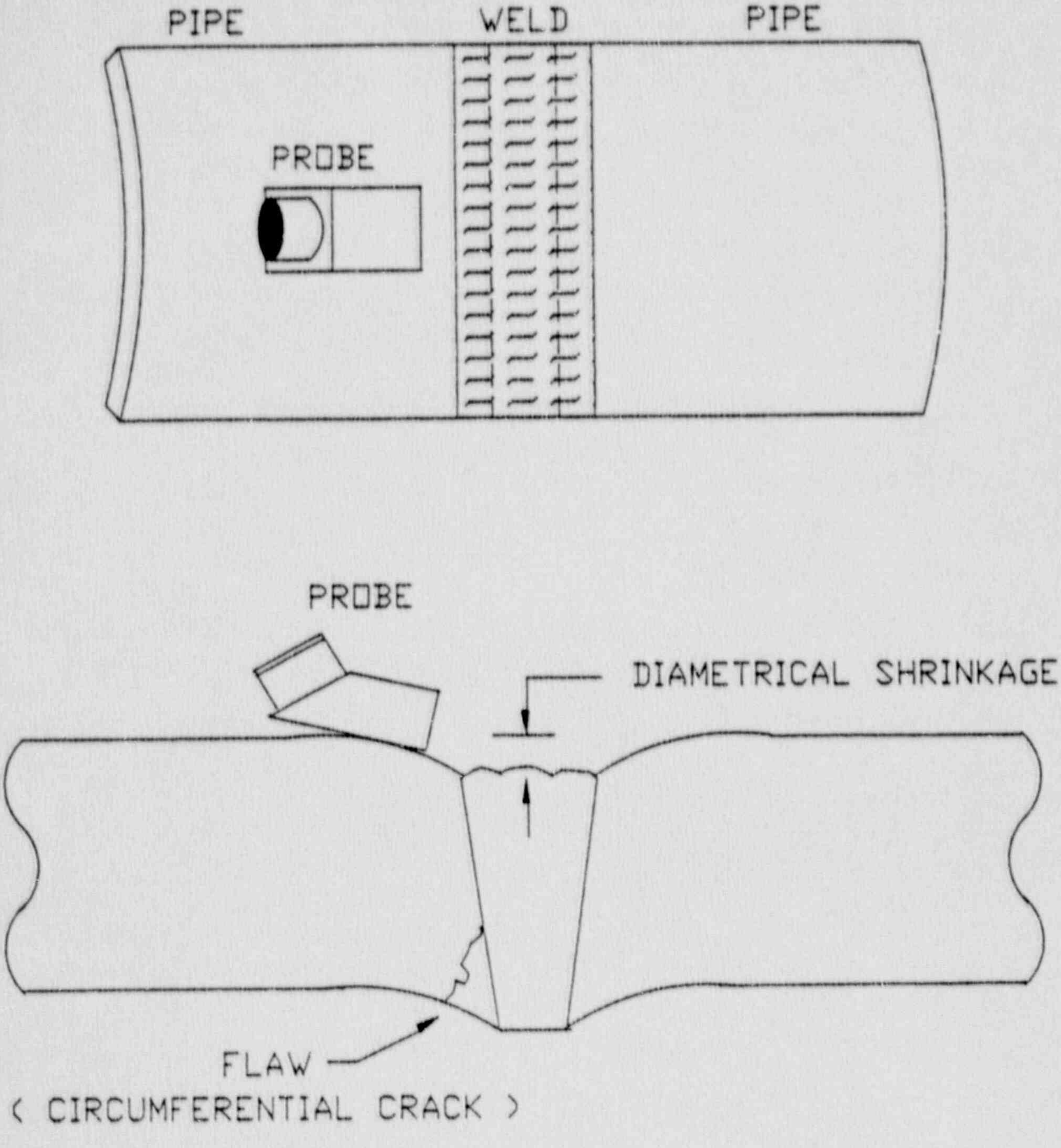


FIGURE 1 DIAMETRICAL SHRINKAGE

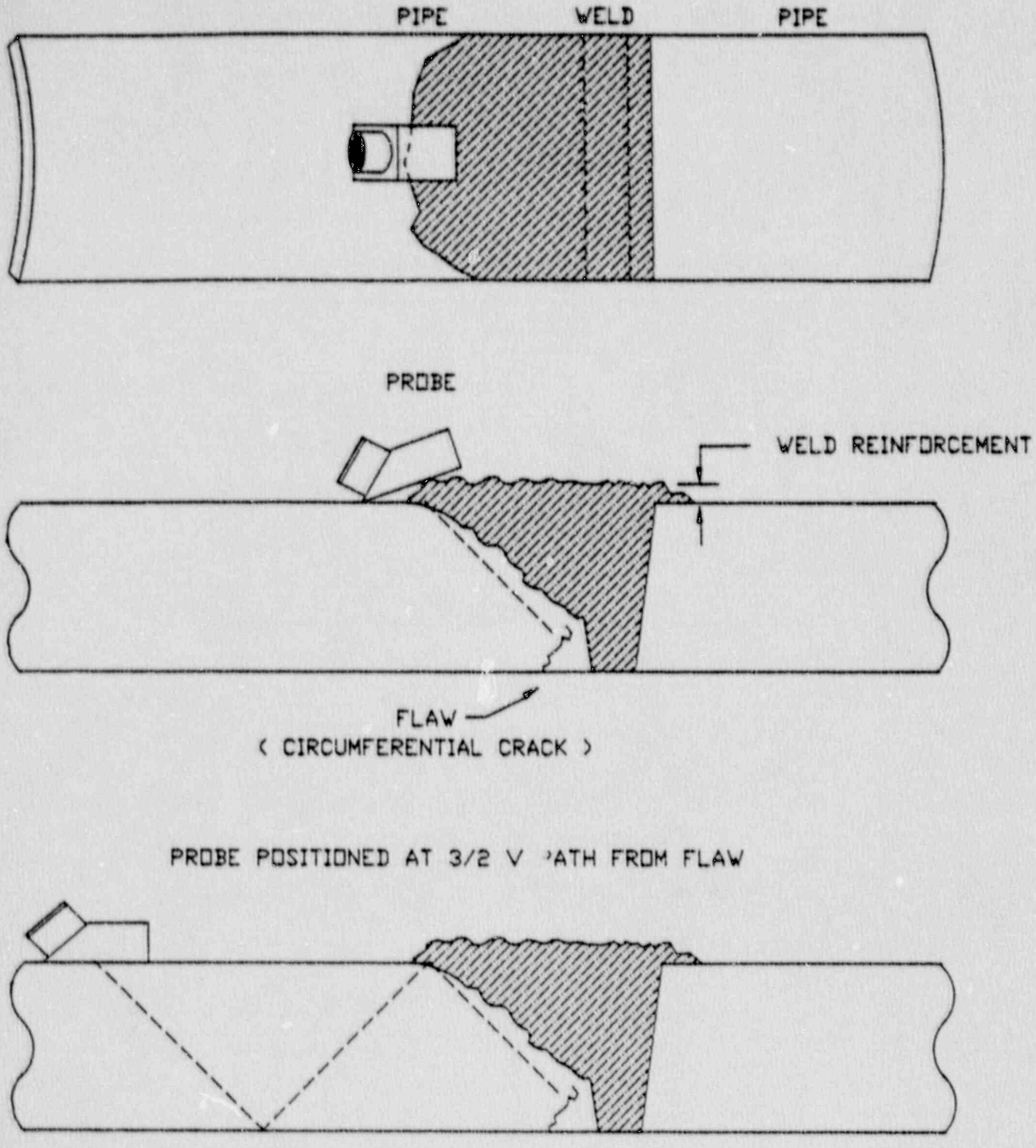


FIGURE 2 EXCESSIVE WELD CROWN

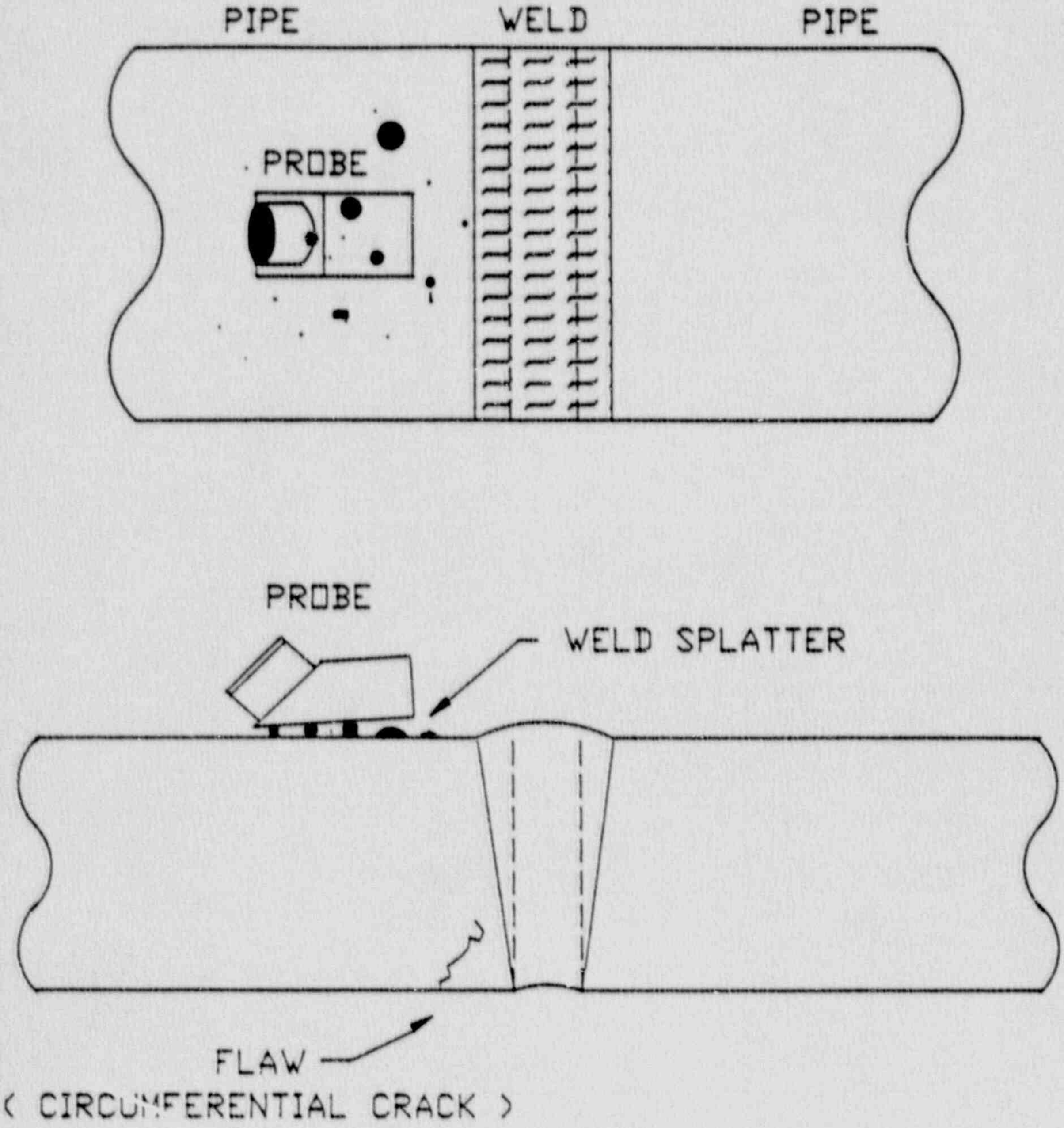


FIGURE 3 WELD SPLATTER

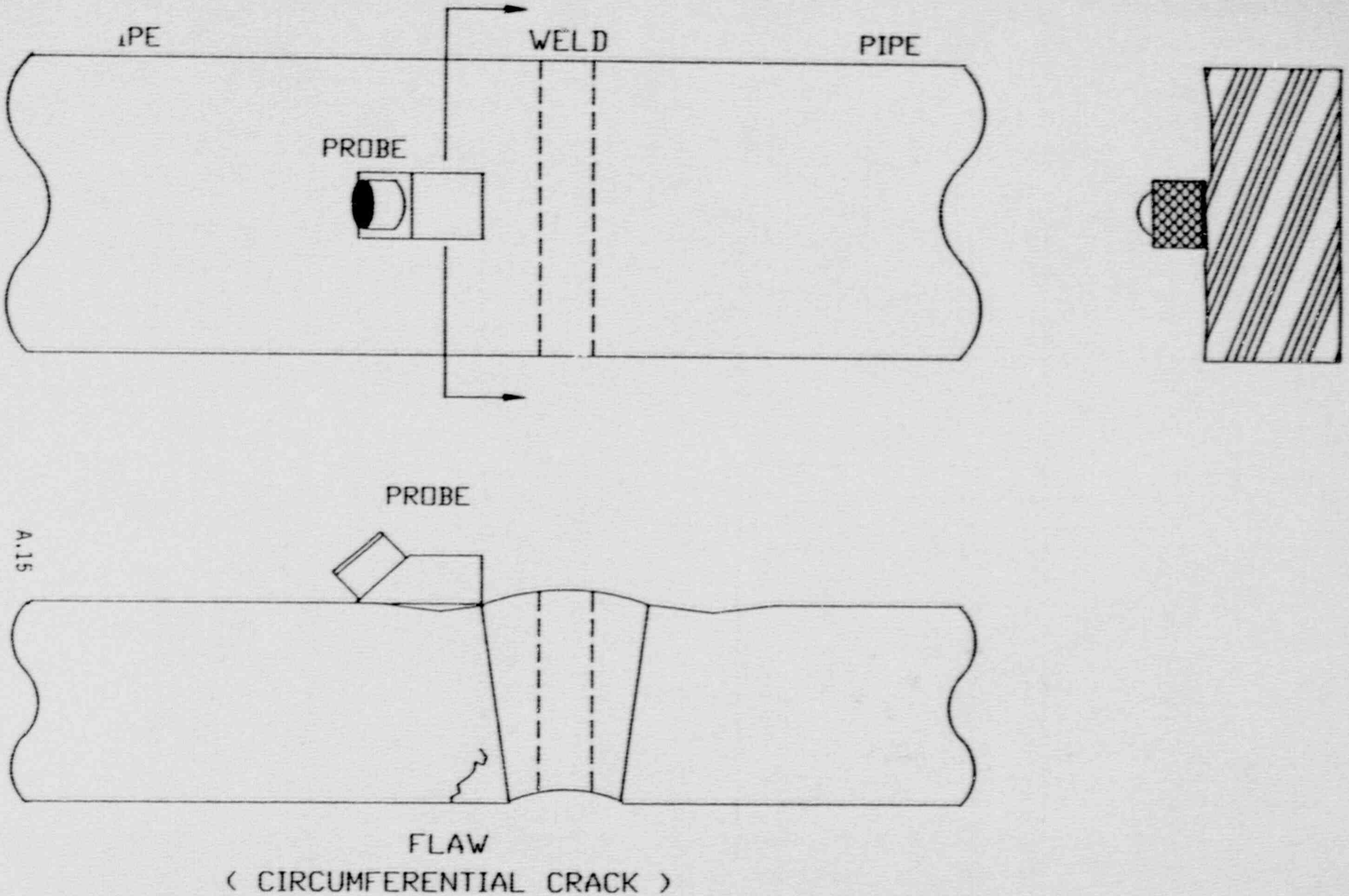


FIGURE 4 OVER - GROUND CONDITION

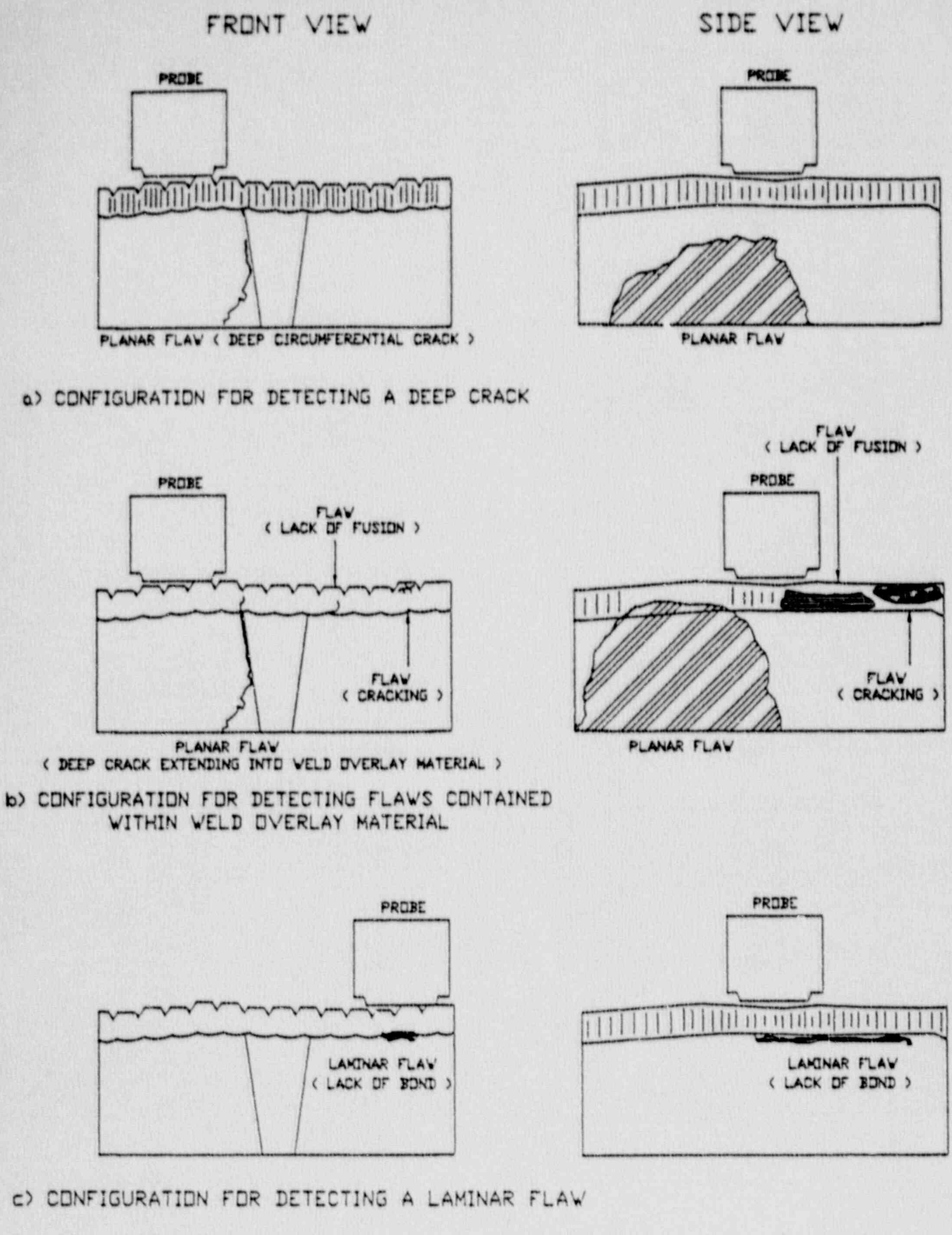


FIGURE 5 WELD OVERLAY

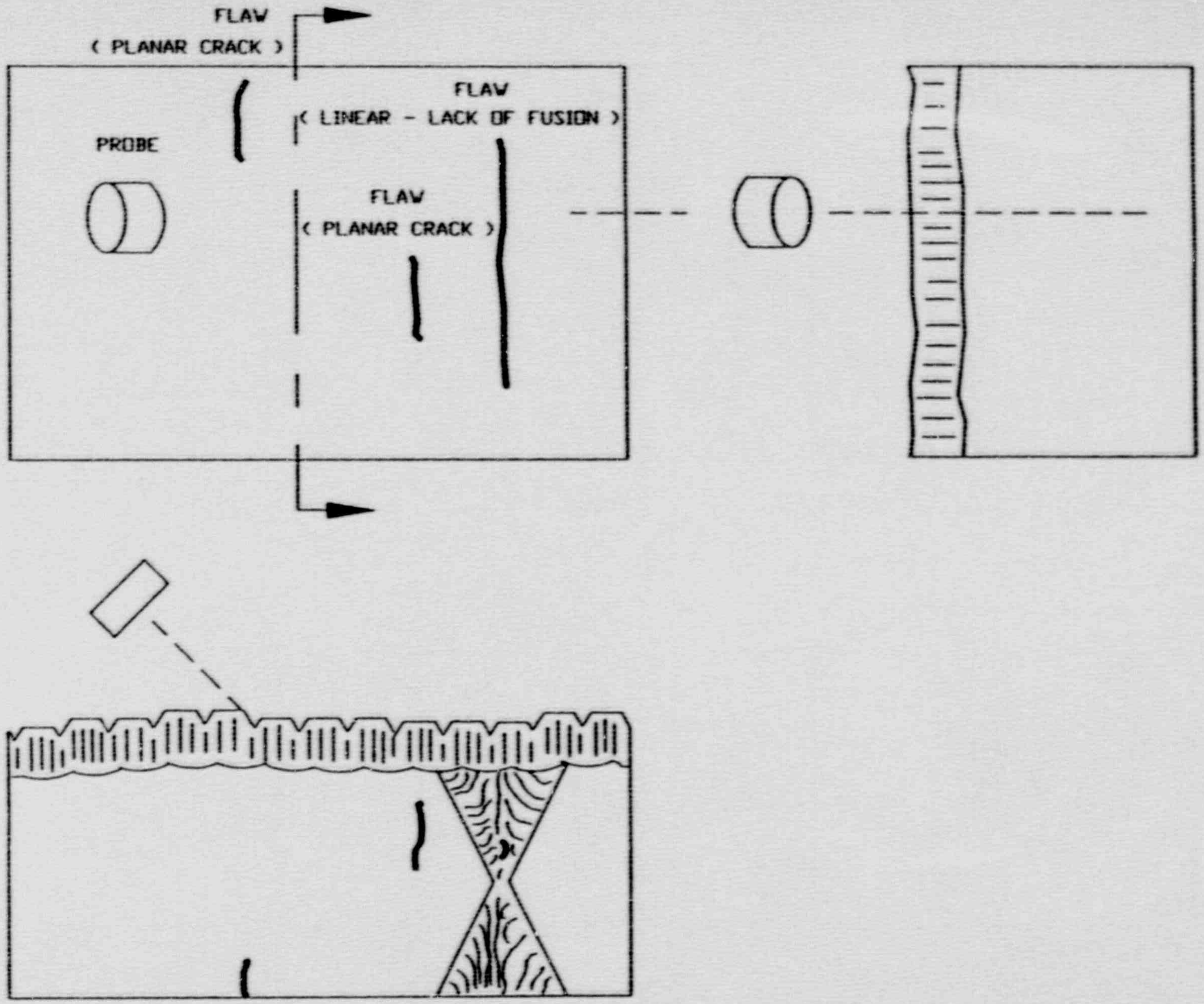
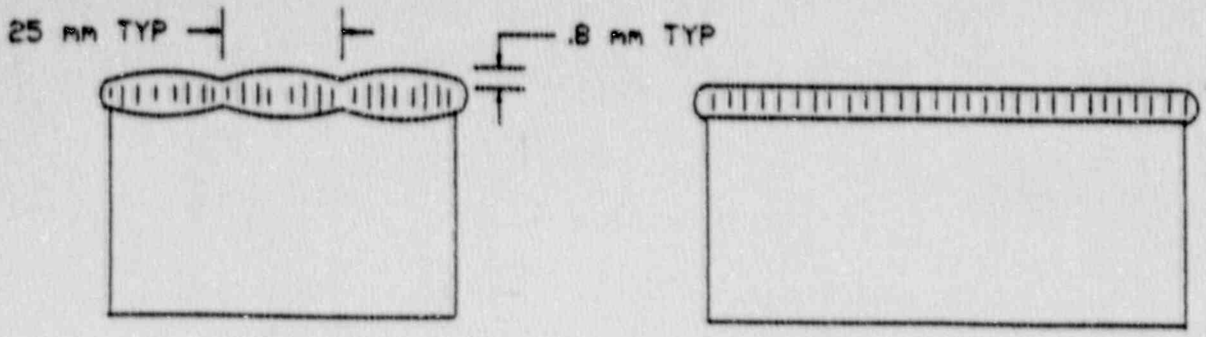
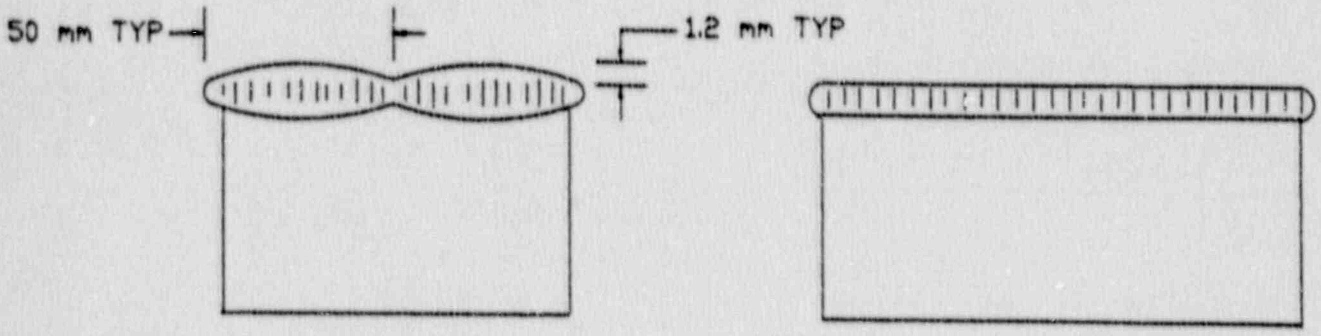


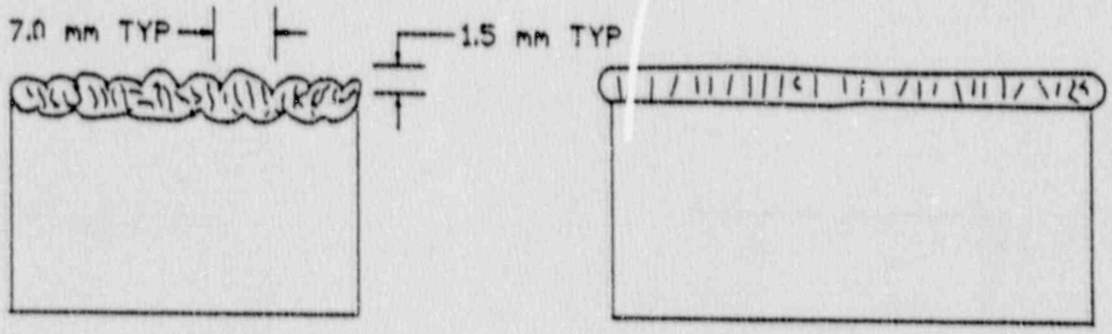
FIGURE 6 PRESSURE VESSEL CLADDING - SINGLE WIRE, MANUAL WELDING



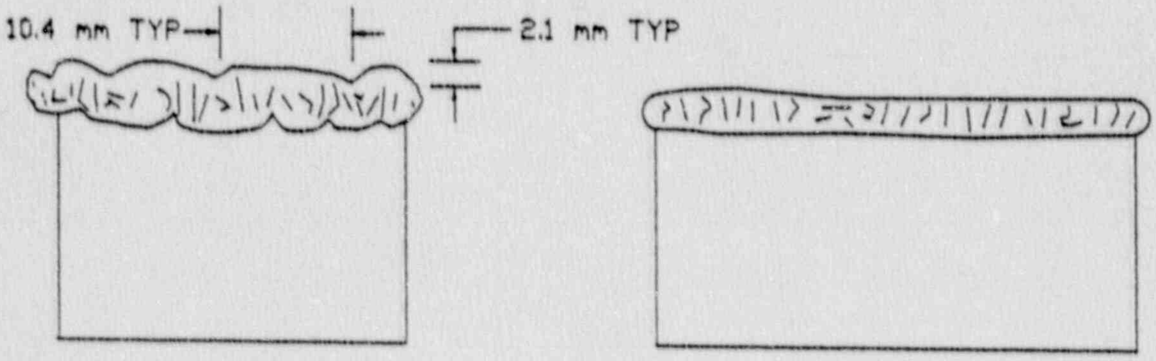
a) AUTOMATED STRIP WELDING - 25 mm STRIP WIDTH



b) AUTOMATED STRIP WELDING - 50 mm STRIP WIDTH



c) MANUAL METAL-ARC WELDING - SMALL WELD BEAD



d) MANUAL METAL-ARC WELDING - COARSE WELD BEAD

FIGURE 7 CLAD SURFACES OF PRESSURE VESSELS

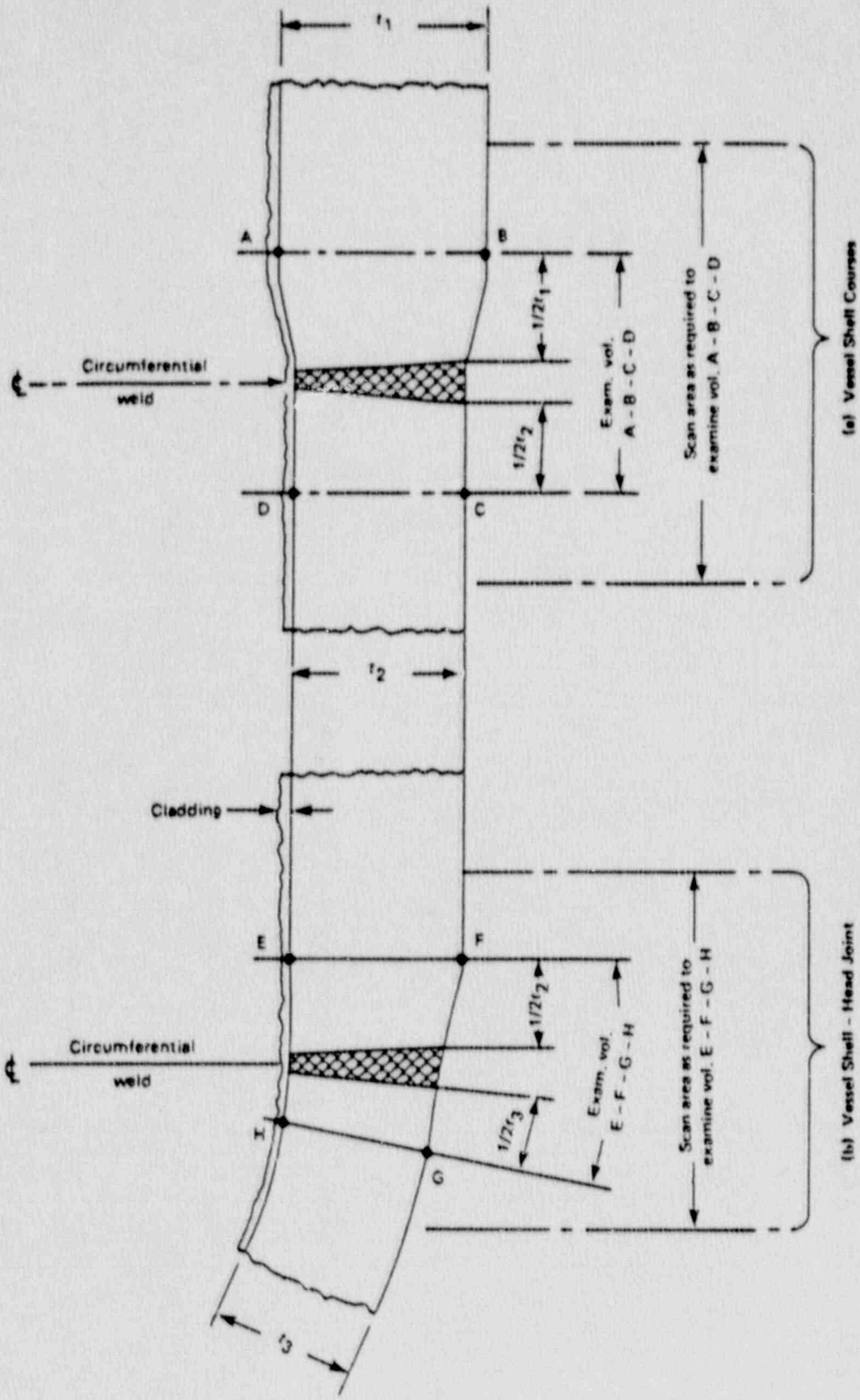


FIGURE 8. FIG. IWB-2500-1 VESSEL SHELL CIRCUMFERENTIAL WELD JOINTS

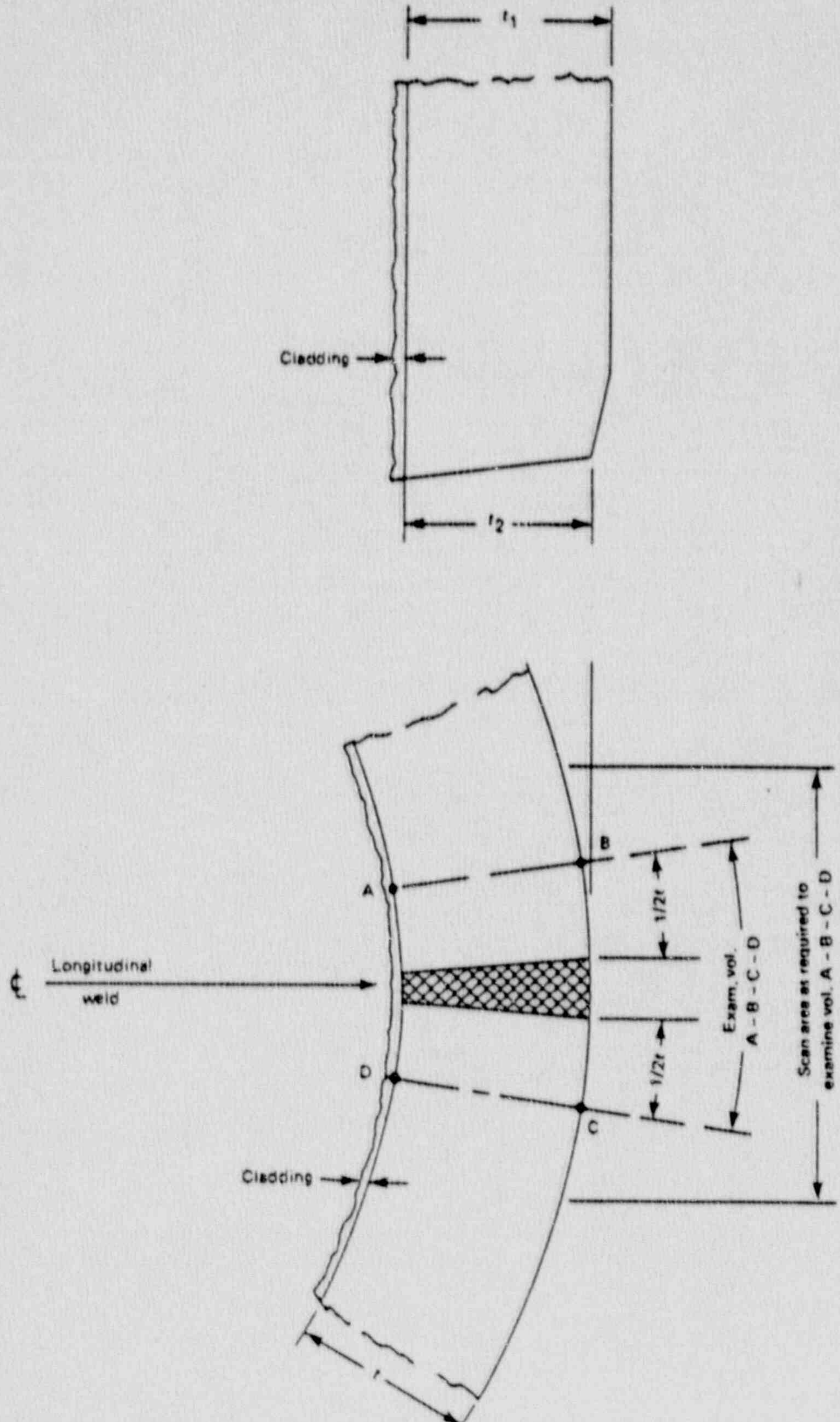


FIGURE 9. FIG. IWB-2500-2 VESSEL SHELL LONGITUDINAL WELD JOINTS

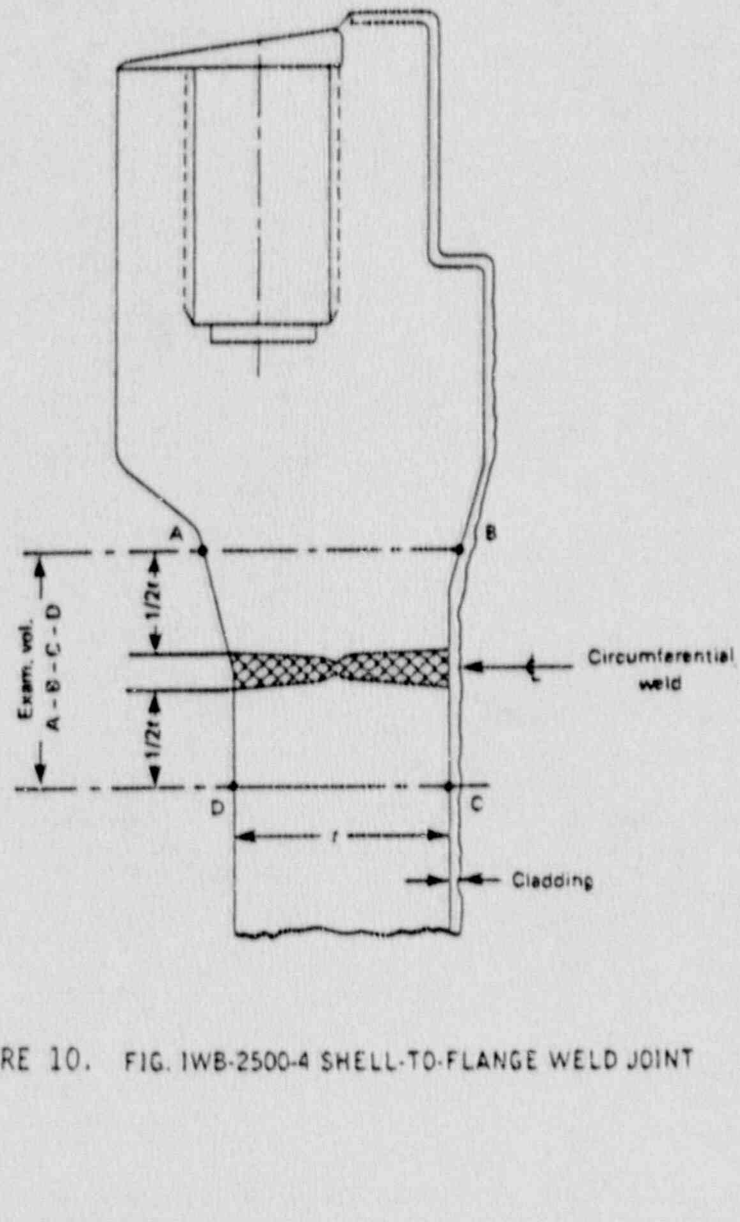
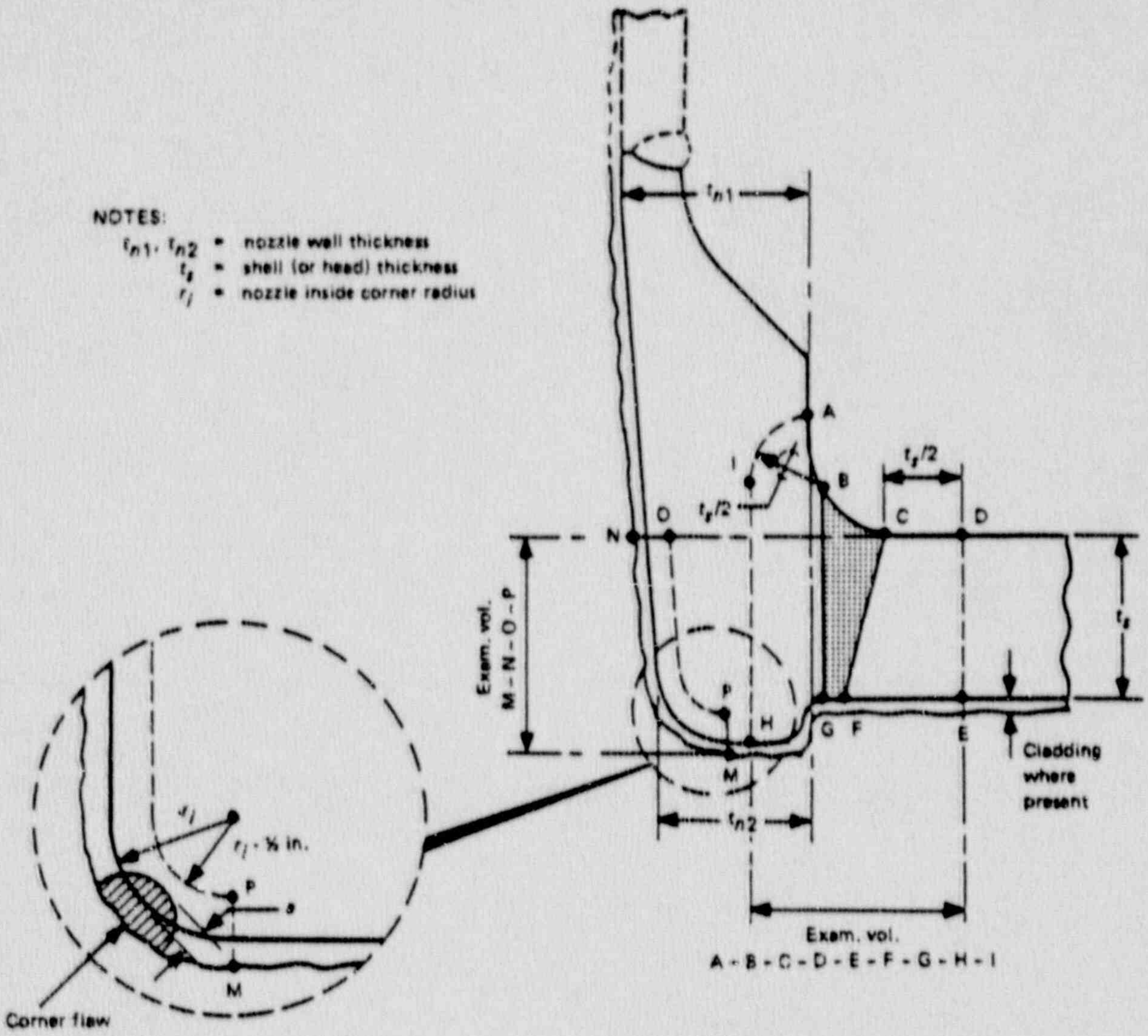


FIGURE 10. FIG. IWB-2500-4 SHELL-TO-FLANGE WELD JOINT



EXAMINATION REGION [Note (1)]	EXAMINATION VOLUME [Note (2)]
Shell (or head) adjoining region	C-D-E-F
Attachment weld region	B-C-F-G
Nozzle cylinder region	A-B-G-H-I
Nozzle inside corner region	M-N-O-P

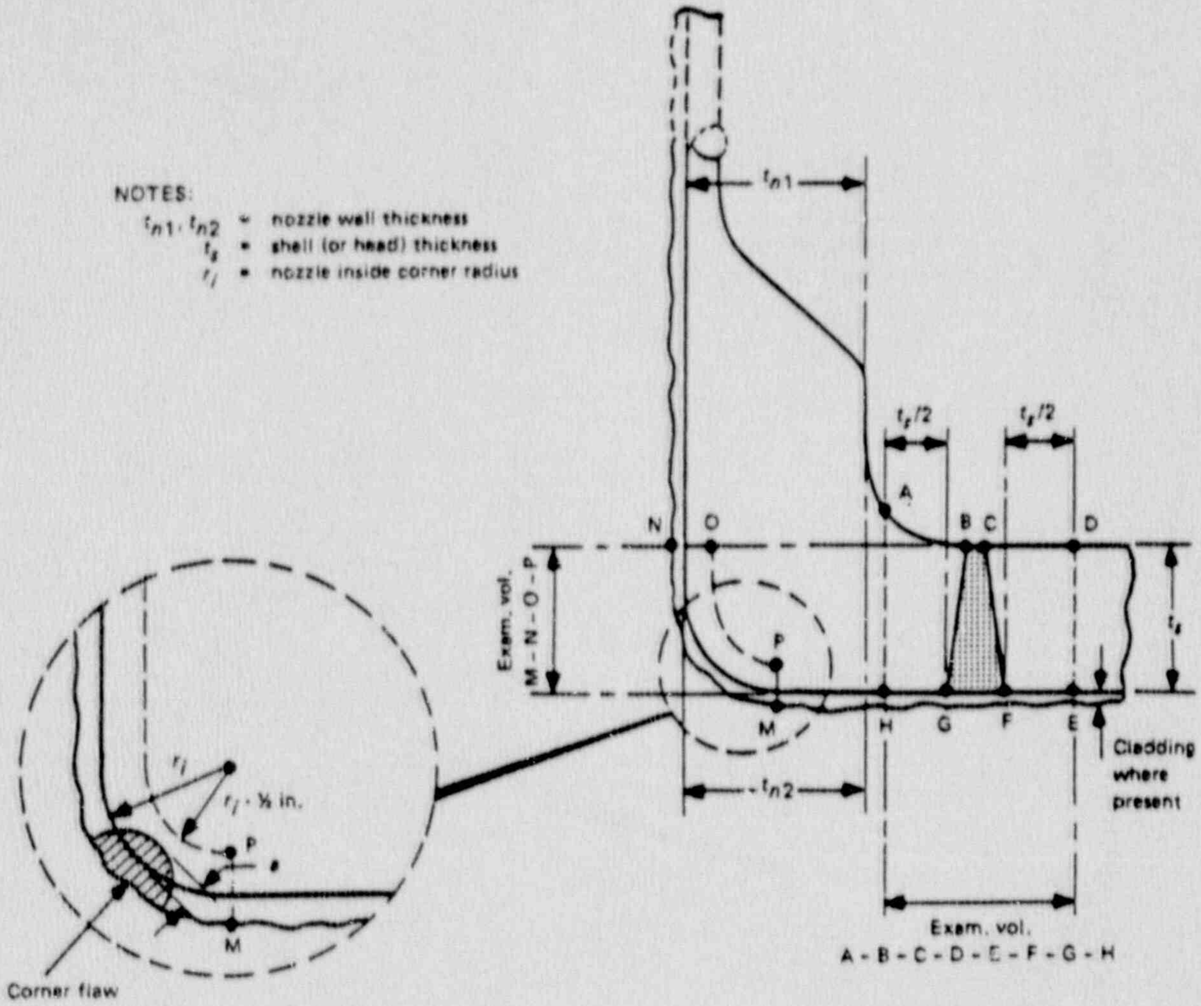
NOTES:

(1) Examination regions are identified for the purpose of differentiating the acceptance standards in IWB-3512.

(2) Examination volumes may be determined either by direct measurements on the component or by measurements based on design drawings.

FIGURE 11. FIG. IWB-2500-7(a) NOZZLE IN SHELL OR HEAD
(Examination Zones in Barrel Type Nozzles Joined by Full Penetration Corner Welds)

NOTES:
t_{n1}, t_{n2} = nozzle wall thickness
t_s = shell (or head) thickness
r_i = nozzle inside corner radius



EXAMINATION REGION [Note (1)]	EXAMINATION VOLUME [Note (2)]
Shell (or head) adjoining region	C-D-E-F
Attachment weld region	B-C-F-G
Nozzle cylinder region	A-B-G-H
Nozzle inside corner region	M-N-O-P

NOTES:
(1) Examination regions are identified for the purpose of differentiating the acceptance standards in IWB-3512.
(2) Examination volumes may be determined either by direct measurements on the component or by measurements based on design drawings.

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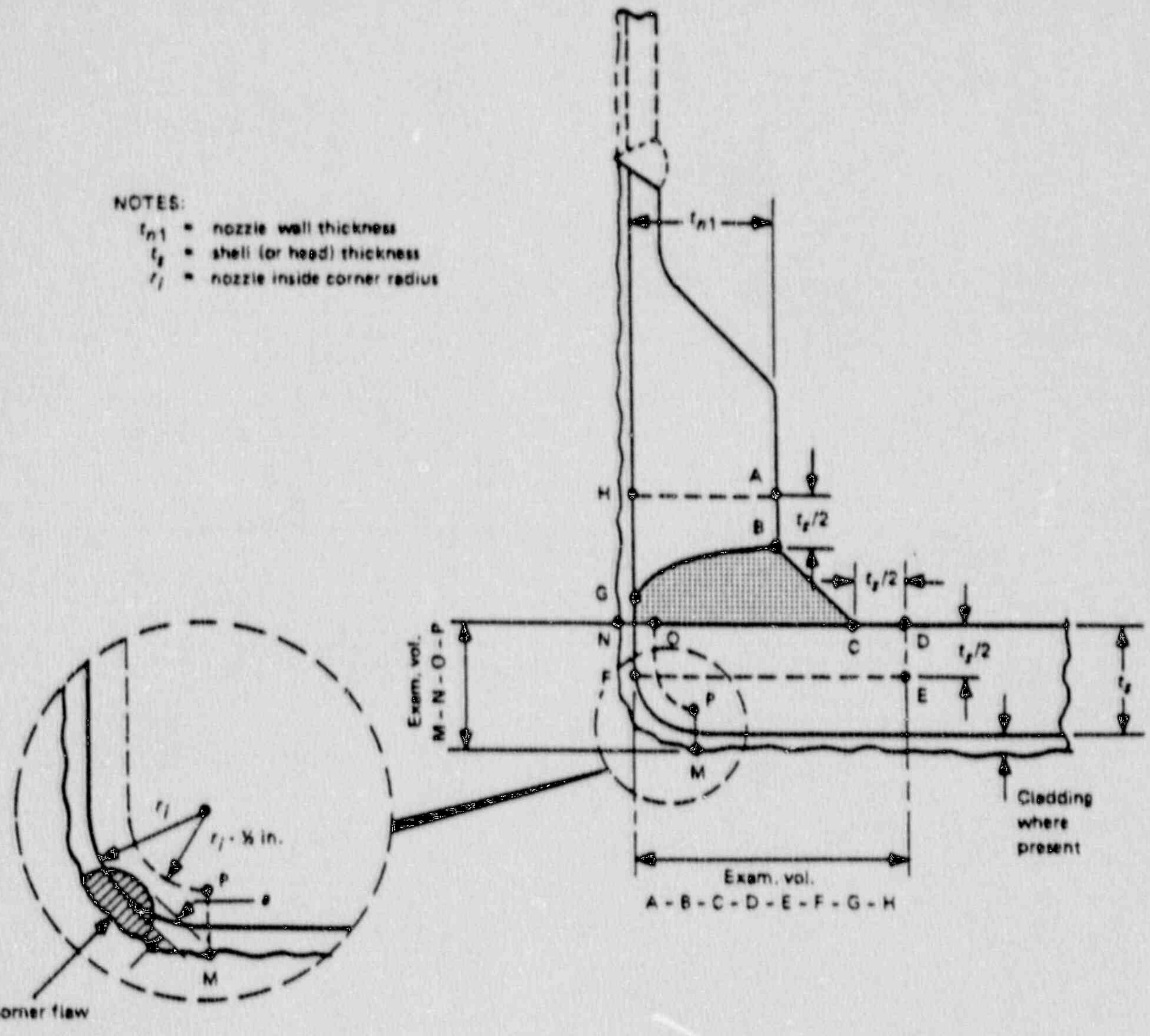
FIGURE 12.

FIG. IWB-2500-7(b) NOZZLE IN SHELL OR HEAD
(Examination Zones in Flange Type Nozzles Joined by Full Penetration Butt Welds)

NOTES:
t_{n1} = nozzle wall thickness
t_s = shell (or head) thickness
r_i = nozzle inside corner radius



EXAMINATION REGION [Note (1)]	EXAMINATION VOLUME [Note (2)]
Shell (or head) adjoining region	C-D-E-F-G
Attachment weld region	B-C-G
Nozzle cylinder region	A-B-G-H
Nozzle inside corner region	M-N-O-P

NOTES:
(1) Examination regions are identified for the purpose of differentiating the acceptance standards in IWB-3512.
(2) Examination volumes may be determined either by direct measurements on the component or by measurements based on design drawings.

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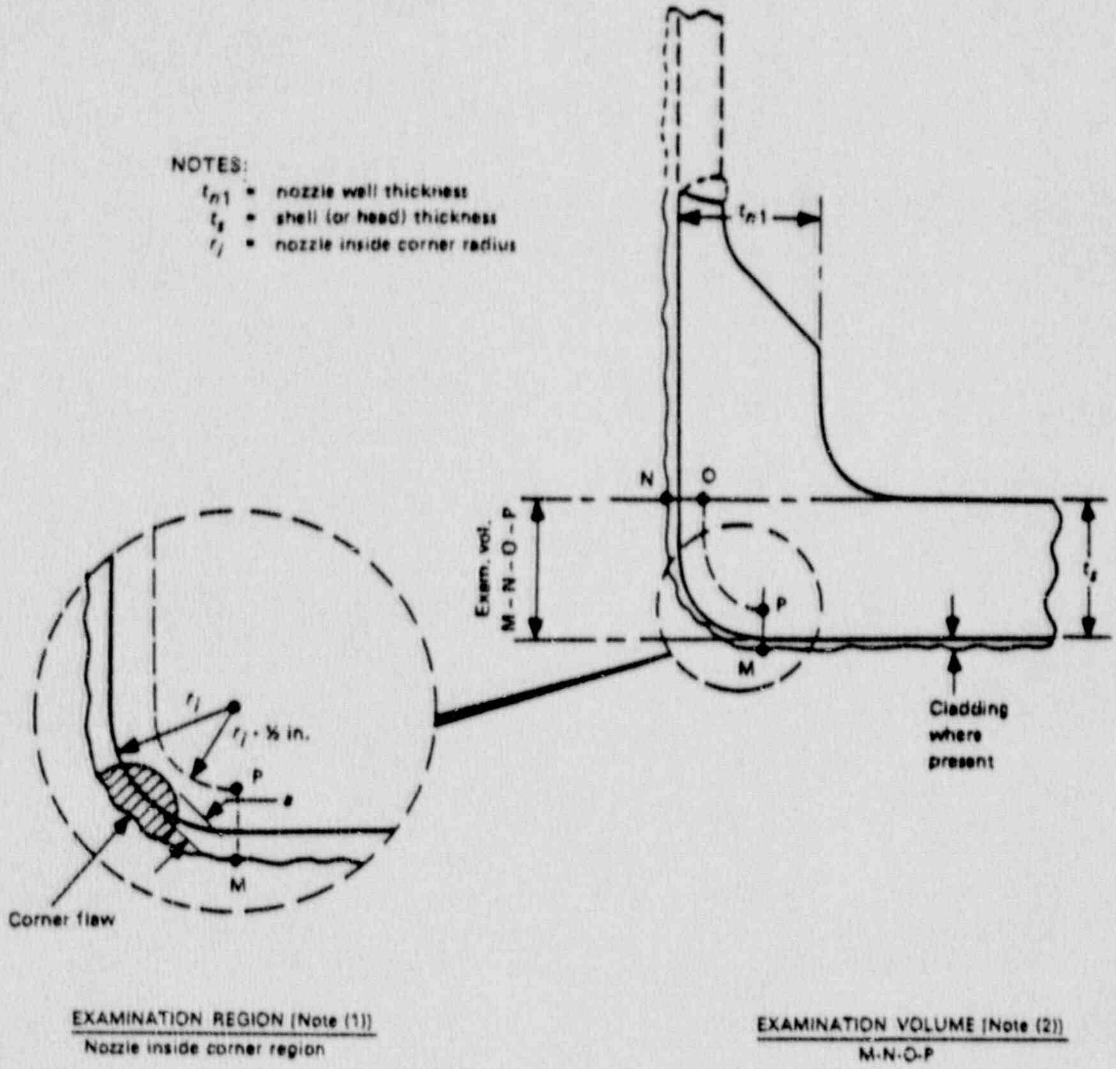
FIGURE 13. FIG. IWB-2500-7(c) NOZZLE IN SHELL OR HEAD
(Examination Zones in Set-On Type Nozzles Joined by Full Penetration Corner Welds)



NOTES:
(1) Examination regions are identified for the purpose of differentiating the acceptance standards in IWB-3512.
(2) Examination volumes may be determined either by direct measurements on the component or by measurements based on design drawings.

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FIGURE 14. FIG. IWB-2500-7(d) NOZZLE IN SHELL OR HEAD
(Examination Zone in Nozzles Integrally Cast or Formed in Shell or Head)

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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 1988 through March 1989.

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