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SUBJECT: RESEARCH INFORMATION LETTER # 113, "RELIABILITY OF INSERVICE INSPECTION FOR PRIMARY PIPING SYSTEMS"

1.0 Introduction

This Research Information Letter (RIL) describes the results of the first phase of a four-phased, 5-year program, being conducted at Battelle Pacific Northwest Laboratory (PNL), entitled, "Integration of NDE Reliability and Fracture Mechanics." Based on these results, four recommendations are presented in this RIL. The implementation of these recommendations should result in a substantial improvement in the effectiveness and reliability of inservice inspection (ISI) for primary piping systems.

The initial phases of the program are focused on ISI of primary piping systems. The objectives of the program include the following:

- Determine the reliability of ultrasonic ISI performed on commercial LWR primary piping systems.
- Using fracture mechanics analysis, determine the impact of nondestructive examination (NDE) unreliability on system safety and determine the level of inspection reliability required to assure a suitably low probability of piping failure.
- Evaluate the degree of reliability improvement that could be achieved using improved and advanced NDE techniques.
- Based on material, service conditions and NDE uncertainties, formulate recommended revisions to ASME Section XI and regulatory requirements needed to assure a suitably low probability of system failure.

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The Phase I effort was directed primarily toward an evaluation of the ASME Code procedures for ISI and identification of major problem areas of primary piping inspection effectiveness and reliability.

Ultrasonic preservice and inservice inspections of primary piping systems are performed under provisions of the ASME Boiler and Pressure Vessel Code, Section XI, "Rules for Inservice Inspection of Nuclear Power Plant Components." Operating reactors currently use either the 1974 Revision of the Code through Summer of 1975 or the 1977 Revision through Summer of 1978. Both revisions have been endorsed by NRC. Inspection procedure requirements are controlled by Appendix III of Section XI and/or Article 5 of Section V. Acceptance standards are specified in IWB 3500.

The acceptance standards of IWB 3500 are based on a conservative methodology using linear elastic fracture mechanics (Reference 1). However, the requirements for ultrasonic inspection provide little assurance that flaws larger than the acceptance standards will be detected. Further, the 1977 revision of the Code resulted in a reduction of inspection sensitivity of 6 to 16 dB (6 dB represents a reduction in flaw signal amplitude by 50 percent, while 16 dB represents a reduction in flaw signal amplitude by 84 percent.) The revision does not appear to be justified based on measurements performed on real and artificial defects of less than optimum reflectivity characteristics (i.e., roughness, tightness and orientation). In addition, the Code provides no guidance in addressing the problems of weld and base metal attenuation which limit the effectiveness of inspections performed on austenitic and dissimilar metal welds.

2.0 Discussion

Approximately 5,000 measurements have been made on artificial (notches) and fatigue flaws in flat plate and pipe samples to determine the influence of inspection variables on the effectiveness and reliability of ISI of primary piping system welds (Reference 2). These data, along with measurements and estimates of operator and inspection team variability, have been used to estimate the effectiveness of current (Section XI, Summer 1978) inspection practices. Measurements of the reduction in ultrasonic inspection sensitivity resulting from use of ASME Section XI 1977 through Summer of 1978, as compared to the 1974 Revision through Summer of 1975, were made on 34 (approximately 500 measurements) pipe inspection calibration standards. The standards ranged in diameter from 4.0 to 30.0 inches and nominal wall thickness 0.237 to 2.343 inches.

Inspection variables investigated in Phase I include the influence of ultrasonic search unit selection, flaw orientation, the influence of counterbore angle, flaw roughness, and flaw tightness. These measurements are described in the Phase I report (Reference 2).

Results of the measurements noted above were used in a model which was developed (Reference 2) to determine the probability that an inservice defect would produce an ultrasonic response sufficiently large to require it to be reported for any given threshold level. Specific inputs to this model are: the expected mean response of flaws as a function of their depth, the variability resulting from flaw characteristics (tightness, roughness and orientation), the variability within an operator (repeatability), and the variability between operators, which was derived from available literature (References 3 and 4). The model has been used to obtain approximations of current levels of inspection reliability. Information gained by the round robin tests to be performed in Phase II of the program will be used to refine and substantiate the inspection reliability model.

3.0 Results

3.1 Ultrasonic Measurements

The results of the measurement program are described in Reference 2 and summarized below. Inspection results using the 1977 Code revision are 6 to 16 dB less sensitive than inspection results from use of the 1974 Code for 45° shear wave inspection. The results of the measurements are shown in Figure 1. The measured results shown in Figure 1 represent the amplitude produced by the side-drilled holes (SDH) (1974 Code) divided by the amplitude produced by notches (1977 Code). The notch reflects a larger amplitude (lower inspection sensitivity) and the ratio (in terms of dB) is negative. The measured data also agree well with theoretical calculations.

The inspection reliability model described in Section 2.0 above was applied to provide baseline estimates of inspection reliability. Inputs used in the calculations are based on measurements performed during the course of this program and are described in Section 7 of Reference 2. The results of these calculations are shown in Figure 2. The calculations are based on inspections performed according to ASME Section XI, Appendix III, 1977 Revision through Summer of 1978. Reporting or corrective action is only required for flaws which exceed 100 percent distance amplitude correction (DAC) level. Probabilities for 50 percent and 20 percent DAC are shown to indicate the reliability improvement which would result from lowering the reporting level.

IMAGE EVALUATION
TEST TARGET (MT-3)

6″

IMAGE EVALUATION
TEST TARGET (MT-3)

6"

The inspection reliability estimates, described above, are based on measurements made primarily on fatigue cracked 0.6-inch wall thickness samples. The measurements were extrapolated to a thickness of 1.8 inches by measurements performed on ideal reflectors. It is estimated that the calculations are applicable over the thickness range of 0.3 inches to 2.5 inches for ferritic piping and flaws in wrought austenitic base material where both sides of the weld are accessible. The estimates do not apply for cast austenitic, dissimilar metal welds or in any case where the sound must propagate through austenitic weld metal. In these latter cases, it is expected that the inspection reliability will be substantially lower. The estimates were based primarily on flaws of aspect ratio (depth/length) of 0.2. The estimates may be overly conservative for long flaws particularly in ferritic pipe greater than 1.5 inches in thickness. It should be noted that the inspection reliability will be measured by the round robin tests in Phase II of the program.

Two general conclusions, from the inspection variability measurements, can be stated. First, real defects can produce reflected amplitudes substantially lower than the ideal reflectors which are used for calibration. Second, reflected ultrasonic amplitudes do not necessarily indicate the severity of the defect, particularly for flaws of less than optimum orientation. Specific conclusions from the measurement program for flaw variability are as follows:

A. ASME Section XI, Appendix III calibration requirements, coupled with a lack of search unit selection and control, provide no assurance that even ideal reflectors of reportable size will produce reportable indication signals.

B. Ultrasonic transparency produced by flaw tightness and/or fluid in the crack can reduce reflected signal amplitudes by as little as 2 or 3 dB to as much as 32 dB. This effect is qualitatively similar to the theoretical calculated reflection from closely-spaced, smooth plane parallel surfaces.

C. Non-optimum orientation of surface-connected reflectors can produce substantial loss in signal amplitudes, compared to ideal reflectors, and exhibit little relationship to reflector through-wall depth for 45° incidence. In all cases, the condition is less severe for 60° incidence. This condition is frequency and search unit dependent.

D. The influence of crack roughness in the range of 10 to 30 μm RMS can reduce reflected signal amplitude by 1 to 12 dB relative to an ideal reflector of the same size. The amplitude decreases monotonically as the degree of surface roughness increases.

3.2 Deficiencies in Inspection Requirements

From a review of the Code (ASME, Section XI, 1977 Revision through Summer of 1978) and the literature, as well as the measurements and evaluation program, several shortcomings in the current inspection requirements are defined. These deficiencies follow.

3.2.1. Calibration Sensitivity

The calibration sensitivity, established by the 1977 Code, is inadequate to assure the reporting of unacceptably large flaws, as defined by IWB 3514. This results from the depth and length of the specified calibration reflector. The sensitivity is also dependent on transducer diameter, which is presently uncontrolled by the Code. The 100 percent DAC reporting level does not allow for the differences between the ideal calibration reflector and real defects. It is generally assumed that larger flaws will produce larger reflected signal amplitudes. This, however, is not the case. Flaws which are rough, tight, filled with water, or of less than optimum orientation may yield substantially smaller reflected amplitudes than ideal reflectors.

3.2.2. Inspection Angle

Nearly all pipes contain a counterbore taper of up to 15°. A flaw located on a 15° counterbore may yield a reflection by as much as 10 dB less than an ideal reflector of the same size using 45° shear wave inspection. This signal loss increases as the flaw size increases. An inspection angle of 45° is required, however, other angles are allowed. Experiments have shown that 60° shear wave inspection is far less sensitive to flaw orientation than 45° inspection. In some cases, 60° shear waves may actually provide larger signal amplitudes for non-optimum flaw orientations.

3.2.3. Sizing

The Code (Section XI, Appendix III, 1977 Revision through Summer of 1978), IWA-2232 (C) (3) states that "the size of reflectors shall be measured between points which give amplitudes equal to 100 percent of the reference level." This technique ignores the fact that flaw tightness, roughness and orientation substantially affect reflected amplitude. Probe motion measurements (6 dB or 20 dB drop techniques) are often used. However, they are also subject to large errors. Measurements made as a part of this program cannot recommend any particular conventional technique capable of accurately sizing flaws over the range of conditions expected in service. Where flaw sizing is to be performed, application of techniques qualified under the particular conditions of that case is appropriate.

3.2.4. Surface Condition and Contour

The Code states only that "the finish on the surface of the calibration sample shall be representative of the surface finish of the piping." This is indeed an important parameter. However, without a statement of maximum allowable surface roughness, reliable inspection cannot be assured. In addition, the surface contour of the weld joint (crown and heat affected zone) may seriously limit inspection effectiveness. The presence of unground or partially-ground weld crowns limits inspection coverage of the required inspection volume. Diametrical shrink present in most welds also limits reliable inspection coverage. Diametrical shrink or surface contour can result in reduction of ultrasonic coupling efficiency as well as a change in the angle of propagation.

3.2.5. Scan Overlap

The Code currently requires that each scan overlap the previous scan by 10 percent of the transducer diameter. Experiments have shown that this overlap is not sufficient to assure recording of rejectable flaws. The overlap problem is particularly acute for automatic scanning procedures where the transducer is scanned parallel to the flaw or where data are recorded only at specified increments of transducer position.

3.2.6. Coverage of Inspection Volume

The requirement of Section XI, Appendix III 4420 (1977 Code) that "the angle beam examination for reflectors parallel to the weld shall be performed by a full Vee path from one side or a one-half Vee path from two sides of the weld, where practicable," does not assure effective inspection over the entire inspection volume. Full Vee path examinations may be adversely affected by counterbore conditions, through beam redirection and loss of energy through mode conversion, and in many instances does not cover the full inspection volume. Three-halves Vee path and other examination angles may be required for full coverage of the inspection volume.

3.2.7. Transducer and Instrument Performance

The Code does not require verification or measurement of transducer or instrument operating characteristics, other than vertical and horizontal linearity and attenuator calibration. Operating characteristics of the inspection system, such as center frequency, bandwidth and effective beam diameter can have considerable influence on inspection effectiveness particularly for flaws of less than optimum characteristics (roughness and orientation). Standardized methods for measuring inspection system performance do not yet exist. However, research is being conducted under this program to develop these methods and acceptance criteria.

3.2.8 Austenitic and Dissimilar Weld Inspection

Items 3.2.1. through 3.2.7. above are equally applicable to ferritic as well as austenitic and dissimilar metal welds. Further, the following items deal with deficiencies in the Code which pertain directly to inspection of austenitic and dissimilar metal welds.

A. The Code (Section XI, Appendix III and Section V, Article 5) does not address the specific difference between inspection of ferritic and dissimilar metal welds or austenitic welds.

B. Difference in attenuation and refracted angle between calibration samples and the pipe base metal can be substantial. This will affect the sensitivity and effectiveness of the inspection.

C. The attenuation of austenitic weld metal is substantially greater than the base material, which results in decreased sensitivity for flaws located within or beyond the weld. For inspections where only one side of the joint is accessible (single side access), flaws located on the far side of the weld may be undetectable (at present sensitivity levels) due to the increased attenuation through the weld metal.

4.0 Recommendations

The program results described above identify major problem areas which limit the effectiveness of preservice and inservice ultrasonic inspection of primary system piping. It should be recognized that this ongoing program cannot, at this time, offer specific recommendations and methods of implementation for each deficiency listed in Section 3.0 above. However, at this time, four recommendations can be made based on the investigations to date. Acceptance and implementation of these recommendations will assure a substantial increase in the effectiveness of primary piping system ISIs. These recommendations are equally applicable to both ferritic as well as austenitic and dissimilar metal weld inspection.

The direction of continuing research and our best estimate of the most appropriate solution for each problem area are described under the Continuing Research subheading.

4.1 Specific Recommendations

4.1.1. Calibration Sensitivity

Calibration sensitivity is regarded as the most serious limitation of the Code (Section XI, 1977 Revision through Summer of 1978). It has been shown that this sensitivity and the reporting levels of the Code are inadequate.

It is, therefore, recommended as an interim measure that the reporting and recording level as defined by Section XI, IWA-2232 and Appendix III be lowered to 50 and 20 percent, respectively, of the primary reference level, for those inspections of pipes with wall thickness equal to or greater than 0.312 inches. This requirement is less stringent than the 1974 Code (Summer of 1975) for piping thickness greater than 0.4 inches and only slightly more sensitive for thicknesses less than 0.4 inches and should, thus, place no undue burden on the inspection process. The relative increase in inspection effectiveness, resulting from this recommendation, can be estimated by comparing the 100 and 50 percent DAC recording probability curves of Figure 2.

The above is recommended as an interim measure for two reasons: (1) to avoid further approvals of ultrasonic inspections at inappropriate sensitivity levels in the near-term, and (2) to allow for development of more appropriate calibration reflectors in the longer term.

4.1.2. <u>Inspection Angle</u>

It has been demonstrated that the effectiveness of 45° shear wave inspection is adversely affected by flaw orientation, while the influence of 60° inspection is considerably less. It is, therefore, recommended that 60° shear wave inspection be required in addition to 45° inspection. Reporting and recording levels of 100 and 50 percent, respectively, are recommended for the 60° inspection. This additional inspection is required to detect flaws of unfavorable orientation, such as those located on a counterbore taper.

This additional requirement, coupled with the lower reporting and recording thresholds for 45° inspection of 4.1.1. above, will further increase the effectiveness of ISIs. The impact of such a requirement cannot be immediately calculated. However, it is known that at least one ISI organization routinely applies 60° in addition to 45° inspection. This organization based their decision on an internal study which indicated that 11 percent of defects detected could only be detected by the 60° inspection.

4.1.3. Sizing

It is not possible, at this time, to recommend any particular sizing technique which would be applicable to all conditions. It is recommended that in cases where flaws are to be accepted by analysis, the sizing techniques and their accuracy be qualified under conditions similar to that of the field application.

4.1.4. Scan Overlap

It is recommended that scan overlap requirements be revised to require that "the scan overlap shall be sufficient to provide recordable signals from minimum sized (length and depth) reportable defects specified in IWB 3500." Response from each recordable defect should then be optimized to establish its response relative to the reporting level.

4.2 Continuing Research

4.2.1. Calibration Sensititivy

Investigations are in progress to establish the most appropriate calibration reflectors as well as the recording and reporting levels. At this time, it is expected that a semicircular notch (a/l aspect ratio equal to 0.5) of depth equal to the allowable flaw size listed in IWB 3514-2 and -3 for preservice examinations will be most appropriate. The short length of the flaw will resolve many of the sensitivity problems associated with transducer selection as well as provide a more suitable calibration sensitivity.

4.2.2. Inspection Angle

Investigations concerning 45° and 60° inspection are continuing. Development of the new calibration reflector, 4.2.1. above may require modification of reporting and recording levels.

4.2.3. Sizing

Investigations are in progress to define the limits of applicability of the various sizing techniques and to establish qualification procedures. Advanced sizing techniques are also under investigation.

4.2.4. Scan Overlap

It is expected that the scan overlap recommendation above is the most appropriate requirement. The semicircular calibration reflector is expected to provide the most suitable method of assuring suitable scan overlap.

4.2.5. Surface Condition and Contour

Insufficient data are available on the quantitative effects of surface roughness and contour, on which recommendations for improved inspection requirements could be based. Investigations are in progress to supply the necessary data.

4.2.6. Coverage of Inspection Volume

Development of an effective requirement to assure adequate coverage of the required inspection volume will require resolution of items 2, 4 and 5 above. Based on current information, it is expected that an analysis based on I.D. and O.D. geometry as well as access conditions will be required for each weld joint.

4.2.7. Transducer and Instrument Performance

While there is considerable information which indicates that transducer and instrument performance can influence inspection effectiveness, definitive information concerning acceptable limits of performance and measurement techniques is not available. Research and evaluations are underway to establish appropriate limits or tests designed to demonstrate system adequacy.

4.2.8. Austenitic and Dissimilar Weld Inspection

It is expected, due to the range of inspection variables involved, that the most suitable method for assuring effective inspection of austenitic or dissimilar metal welds, will be through a program for procedure and personnel qualifications. Guidelines and requirements for such a program are under investigation. It is expected that samples containing artificial defects as well as defects typical of those found in service will be required. Specific qualification requirements and methods of defect fabrication are currently under investigation. Techniques designed to compensate for weld metal attenuation and differences between the calibration sample and the pipe base metal are also under investigation.

Immediate goals of this ongoing research program include the resolution of research areas described above as well as conducting the "round robin inspection" for the determination and validation of the reliability and effectiveness of primary piping system inspection, and the establishment of guidelines for procedure qualification. In the longer term, it is expected that recommendations will be developed which will provide the necessary assurance of system safety through effective application of ISI techniques.

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Enclosures:
1. Figure 1
2. Figure 2

References

1. Maccary, R. R., "Nondestructive Examination Acceptance Standards, Technical Basis and Development of Boiler and Pressure Vessel Code, ASME Section XI, Division 1," prepared for American Society of Mechanical Engineers, published by the Electric Power Research Institute, NP-1406-SR, May 1980.

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3. Silk, M. G., "Estimates of the Magnitude of Some of the Basic Sources of Error in Ultrasonic Defect Sizing," AERE-R-9023, February 1978.

4. Foreli, O., "Comparison of Radiography and Ultrasonic Testing," 2nd Nordiske NDT Symposium, Kobenhaun, May 21-23, 1979.

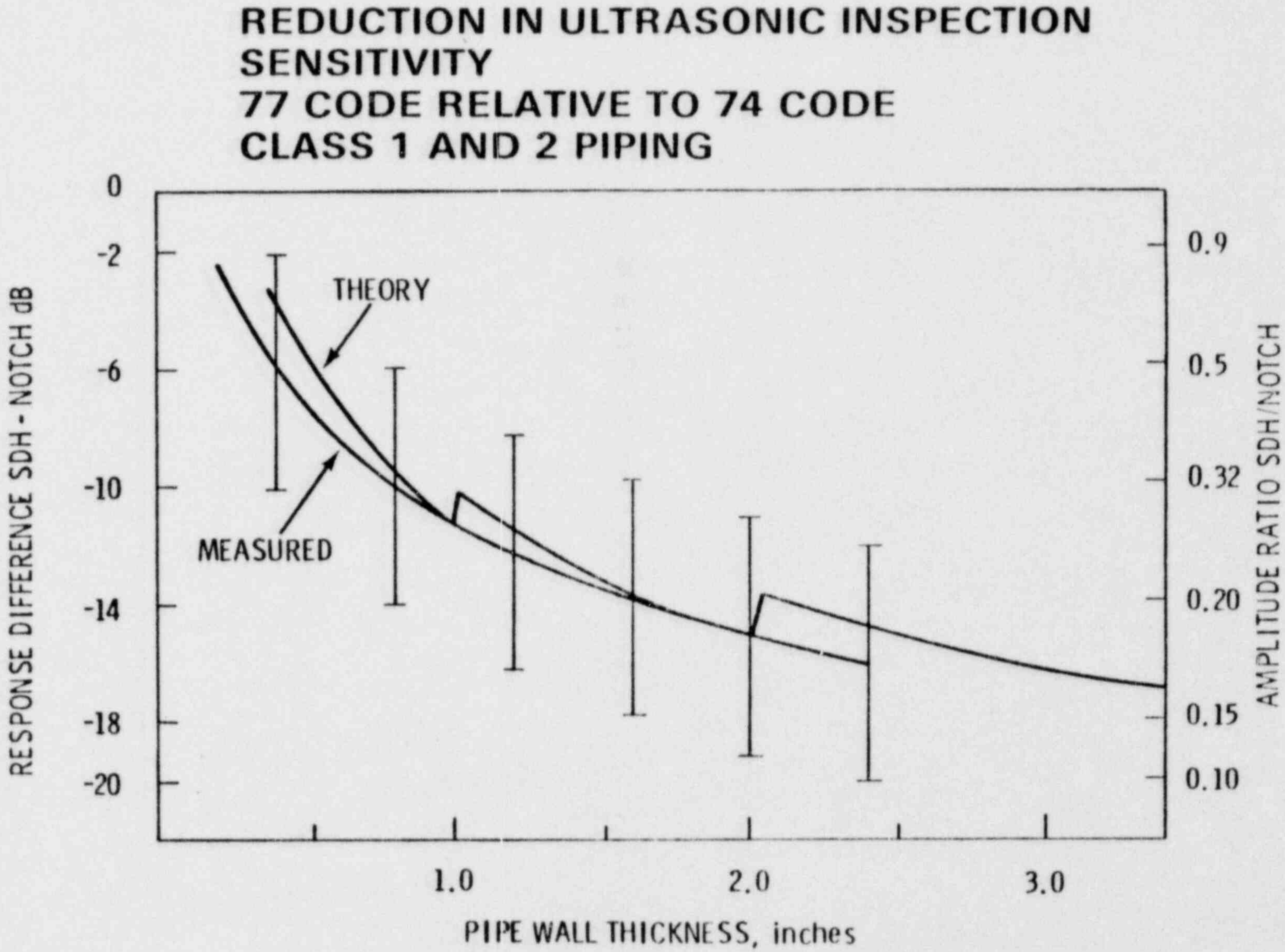

Figure 1. Measured and theoretical reduction in ultrasonic piping inspection sensitivity of the 1977 edition of the ASME Code, Section XI, as compared to the 1974 edition, using notched and side-drilled hole calibration specimens, respectively.

POOR ORIGINAL

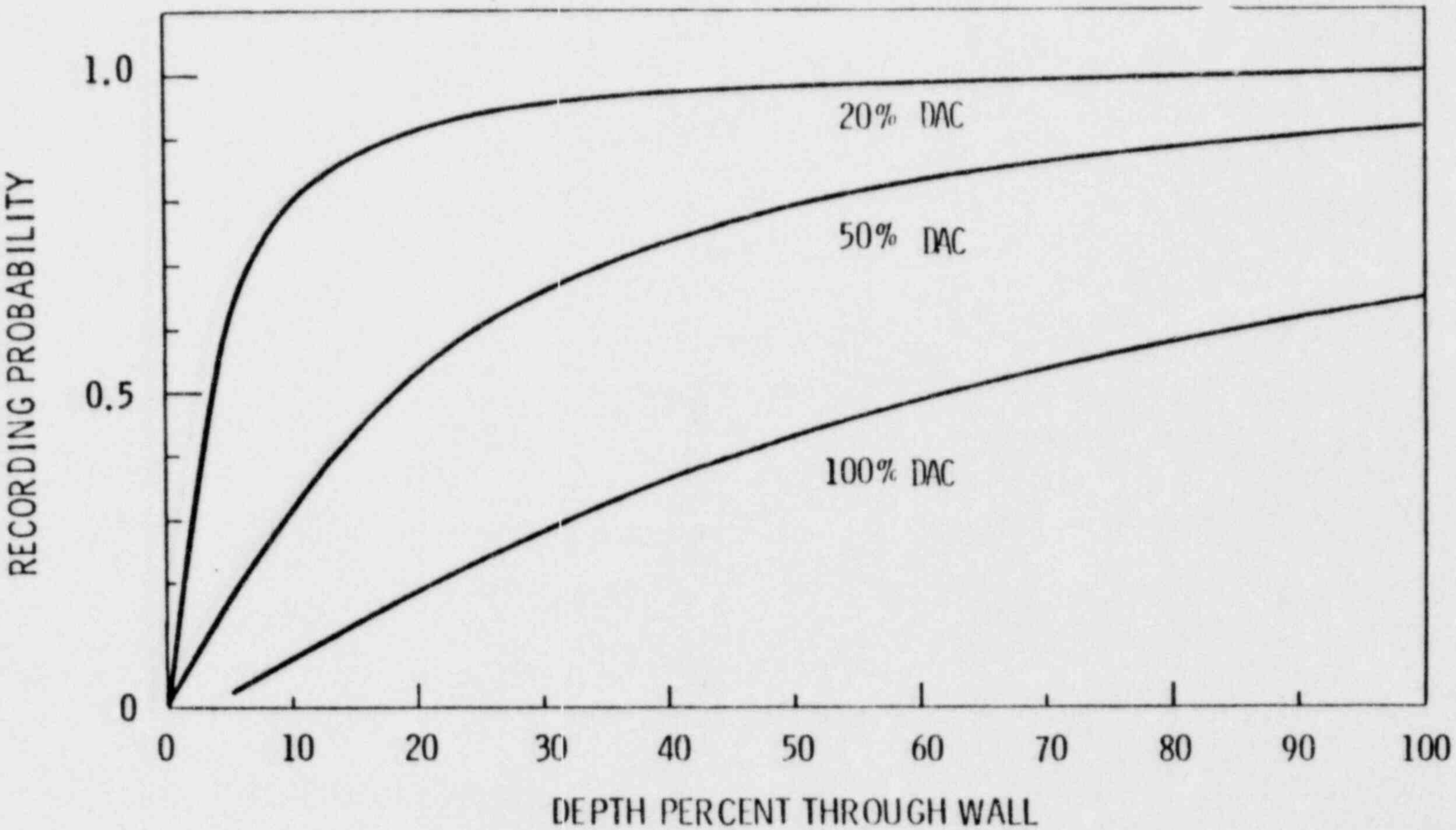

Figure 2. Estimated Recording Probability (i.e., the probability that the ultrasonic response will exceed a threshold value) versus flaw depth for 100, 50 and 20 percent DAC recording or reporting thresholds for piping wall thickness of approximately 0.3 through 2.5 inches.