# DETECTION AND DISPOSITION RELIABILITY OF ULTRASONICS AND RADIOGRAPHY FOR WELD INSPECTION

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## INTRODUCTION

Since the 1940's, the U.S. Navy has used radiography (RT) as the inspection method for structural welds. The major advantage of radiography compared to other inspection techniques is the availability of objective quality evidence, the radiograph, as a permanent record of the inspection. Radiography has gained precedence as the inspection method to prescribe for critical welds because this permanent record is perceived to evince all discontinuities and the disposition of discontinuities is perceived to be highly accurate. This technique and the criteria used to accept or reject discontinuities have generally proved adequate, although technical limitations have been identified [1].

Ultrasonic inspection (UT) of structural welds was formally introduced into the Navy in 1962. The ultrasonic inspection of weld areas inaccessible to radiography was permitted with the caveat that "in no case shall the quality acceptance criteria be lower than the radiographic criteria." The limited acceptance of ultrasonic inspection for structural welds is due, historically, to the lack of permanent objective quality evidence, the purported inconsistency of inspection results, and the reputation that ultrasonics does not readily detect volumetric discontinuities (i.e., porosity or slag) and rejects more planar discontinuities (i.e., cracks or lack of fusion) than RT.

The benefits of using ultrasonic inspection instead of radiography include the following: cost savings through increased productivity, immediate inspection results, and information concerning the depth of rejectable defects. Losses in shipyard productivity are associated with the use of radiography for the following reasons: (1) safety regulations require that work within radiation hazard zones be delayed until the radiographic inspections are complete, and (2) inspection results are not immediately available as the radiographic film must be processed and interpreted before the inspection is complete. On the other hand, the use of ultrasound increases productivity. There are no safety hazards associated with the ultrasonic inspection so that work in adjacent areas is not precluded and the inspection results are available immediately as the ultrasonic operator inspects, interprets, and dispositions the weld at the time of the inspection. UT also provides information concerning the

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depth of rejectable discontinuities relative to the inspection surface, and guides the selection of the side from which to grind; standard practice radiography does not provide this information. Additionally, with the use of computer assisted ultrasonic inspection systems, permanent objective quality evidence is readily available and the potential exists for more accurate sizing of discontinuities through the use of sophisticated software such as synthetic aperture focussing techniques. As a whole, increased productivity will ensue as a result of using ultrasonics to inspect structural welds.

With the benefits of using ultrasonic inspection in mind, this work was performed to determine if welds may be ultrasonically inspected with detection and disposition reliability comparable to that currently obtained with radiography.

## PROCEDURES

### Approach

Standard practice manual ultrasonics (MUT), radiography (RT), and computer assisted ultrasonics (CAUT) were compared by inspecting 5 steel welds with purposely induced discontinuities. Eight shipyard inspectors performed the manual ultrasonic and computer assisted ultrasonic inspections of the welds. Similarly, eight interpreters reviewed the weld radiographs produced by Ir-192 with Kodak type AA film. The welds were also inspected by a single CAUT operator who had a high level of experience using the system. Consensus discontinuities were identified by reviewing all of the inspection results, classified as to type, and verified by sectioning and metallography. This information was used to document the following: the ability of UT and RT to detect discontinuities of specific types and sizes; the probability of accepting or rejecting specific discontinuity types and sizes using current UT and RT acceptance criteria; the repeatability of the inspection methods; and type I and II errors.

### Weld Fabrication

Five steel test plates (24 x 24 x 1 1/2-inch thick) were welded with purposely induced discontinuities. The weld joint design was a single-V butt joint with an included angle of 60°, a root gap opening of 3/16-inch, and a 1/8-inch land. Shielded metal arc and automated and semi-automated gas metal arc welding processes were used to fabricate the welds with the following types of defects: slag, lack of fusion, incomplete penetration, cracks, clustered porosity, and scattered porosity.

### Ultrasonic Test Procedure

The manual ultrasonic inspections were performed using Krautkramer-Branson USL-48 ultrasonic instruments and the computer assisted ultrasonic inspections were performed using a Danish Welding Institute P-scan system (model PSP-3) with a manual weld scanner (model MWS-1). Both types of inspections used a 3/4 x 1-inch, 2.25 MHz transducer along with a wedge with a 60° effective angle in steel. The systems were calibrated by determining the sound beam exit point, the beam angle, the range/index delay, a distance amplitude correction, and test sensitivity. The test sensitivity was set on the basis of the response of the system to a 3/64-inch diameter side drilled hole. The ultrasonic procedure for evaluating and dispositioning discontinuities required the use of signal amplitude (in percent full screen height (FSH) for the USL-48 inspections and in dB for the P-scan inspections), length, proximity or a combination of the three measurements. Any discontinuity whose signal amplitude was less than 20% FSH or -12 dB was not evaluated. Any discontinuity whose signal amplitude exceeded 80% FSH or 0 dB was rejected. Any discontinuity whose signal amplitude was greater than or equal to 20% FSH or -12 dB and less than or equal to 80% FSH or 0 dB was evaluated based on length or length and proximity as follows: (a) discontinuities greater than 1/2T (T=thickness) were rejected; (b) adjacent discontinuities separated by less than 2L of sound metal (L=length of longest discontinuity) were considered a single discontinuity. The length of the discontinuity was established using the half amplitude method. If the half amplitude was below 20% of full screen height, the extremity of the discontinuity was marked where the indication crossed the 20% level. There was no attempt to classify discontinuities according to type, for example, porosity, slag, etc.

Radiographic Test Procedure

Radiography for this investigation was performed in accordance with standard shipyard practice. The procedure used defined requirements for weld surface preparation, location markers, film, screens and filters, film identification, radiation sources, penetrameters, shims, radiographic quality levels, and reporting requirements. The radiation source for the exposures was Ir-192, and the film was Kodak type AA. According to the acceptance criteria used in the radiographic procedure cracks of any size were unacceptable, while slag, lack of fusion, and porosity were subject to size, proximity, and accumulated length determinations. Figure 1 shows the radiographic acceptance criteria for lack of fusion and slag.

Flaw Identification Procedure

Ultrasonic and radiographic inspectors reported their findings on a common report form. The test reports were reviewed, and a consistent set of flaw identifications was assigned so that the same flaw reported by different inspectors was given a unique identification. This unique

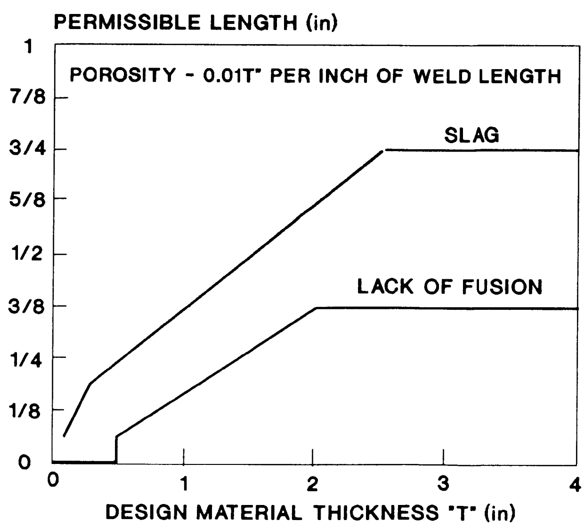



Fig. 1. Radiographic acceptance criteria for porosity, slag, and lack of fusion.

identification was given only to "consensus" discontinuities; that is, discontinuities that were detected by a majority of inspectors or interpreters using at least one of the inspection techniques. Each discontinuity was given one of four labels (listed from most to least severe): crack (CRK), lack of fusion (LOF), slag (SLG), and porosity (POR).

Flaw Verification Procedure

The welds were sectioned in the following manner. The weld metal, heat affected zone, and adjacent base plate were cut from the test plates. The approximate locations of the consensus discontinuities were marked on the weld so that longitudinal or transverse cuts could be made at the approximate extremities of the discontinuities. Each face of the macro-sections was ground, polished, and, if necessary, etched with a 5% nital solution. All consensus discontinuities were identified and classified by examining the faces of the macro-sections with the unaided eye and with magnifications of up to X10. The length of each discontinuity was measured to determine its disposition. Photomacrographs or scale drawings were prepared.

## RESULTS AND DISCUSSION

A total of 34 discontinuities were found in the five plates that were sectioned. The breakdown of the data for those 34 discontinuities is presented in Table 1 as follows: the "VISUAL TYPE" indicates the actual discontinuity type as determined by visual examination; the "NDE TYPE" indicates the discontinuity type as determined through NDE; "MET LENGTH, in." is the actual discontinuity length as determined through sectioning; the "METALLOGRAPHIC DISPOSITION" columns show the actual disposition of each discontinuity as evaluated using both the UT and RT acceptance criteria; the "REJECTABLE DISCONTINUITY" column shows whether a discontinuity is considered rejectable when the most stringent acceptance critieria is applied; the "NDE DISPOSITION" columns show the disposition of each of the discontinuities as called by MUT, Ir/AA and CAUT using the appropriate acceptance criteria (i.e., UT acceptance criteria for MUT and CAUT data, and RT acceptance criteria for Ir/AA data). The CAUT inspections are broken down into the following two categories: "CAUT" indicates the inspection as performed by eight shipyard inspectors, and "CAUT*" indicates the inspection as performed by a single experienced operator of the P-scan. As shown in this table, when the UT and RT acceptance criteria are applied to the metallographic data, more of the discontinuities are rejected by RT than UT. This disparity is due to the fact that the UT and RT acceptance criteria are written such that they allow different discontinuity lengths.

Table 2 summarizes the results concerning the discontinuities identified as rejectable in Table 1. This table itemizes the number of planar, volumetric and total rejectable discontinuities detected; the number of planar, volumetric, and total rejectable discontinuities dispositioned correctly according to the appropriate acceptance criteria; and the number of planar, volumetric, and total rejectable discontinuities not detected or incorrectly dispositioned according to the appropriate acceptance criteria. The data indicates that ultrasonics detects more of the rejectable discontinuities, regardless of the discontinuity type, than Ir/AA radiography. The data also indicates that ultrasonics performed by experienced operators correctly dispositions (according to the appropriate acceptance criteria) these discontinuities at least twice as reliably as Ir/AA radiography. Finally, this table indicates that ultrasonics has fewer misses or incorrectly dispositioned discontinuities than Ir/AA.

Table 1 - Results of metallography

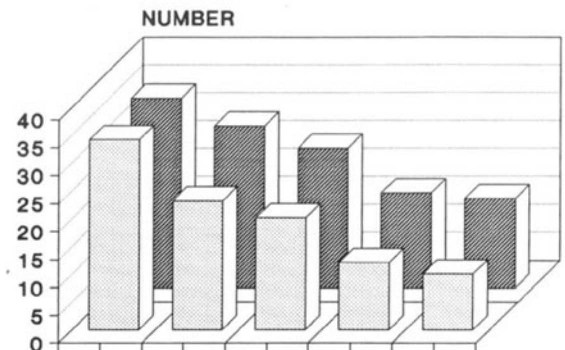
| VISUAL TYPE | NDE TYPE | MET LENGTH, in. | METALLOGRAPHIC DISPOSITION ACCEPTANCE CRITERIA USED: RT | UT | REJECTABLE DISCONTINUITY YES/NO | NDE DISPOSITION INSPECTION TECHNIQUE USED: MUT | Ir/AA | CAUT | CAUT* |
|---|---|---|---|---|---|---|---|---|---|
| CRK | CRK | 0.15 | R | A | YES | ND | R | ND | ND |
| CRK | CRK | 0.5 | R | A | YES | ND | R | ND | A |
| CRK | CRK | 0.55 | R | A | YES | ND | R | ND | A |
| CRK | LOF | 1.2 | R | R | YES | R | ND | R | R |
| LOF | LOF | 0.47 | R | A | YES | A | ND | ND | A |
| LOF | LOF | 0.55 | R | A | YES | A | ND | ND | A |
| LOF | LOF | 0.65 | R | A | YES | A | ND | ND | A |
| LOF | SLG | 0.7 | R | A | YES | ND | A | ND | ND |
| LOF | LOF | 0.71 | R | A | YES | A | ND | ND | A |
| LOF | LOF | 0.72 | R | A | YES | A | ND | ND | A |
| LOF | LOF | 0.79 | R | R | YES | R | ND | A | R |
| LOF | LOF | 0.89 | R | R | YES | R | ND | A | A |
| LOF | LOF | 0.9 | R | R | YES | A | R | A | A |
| LOF | POR | 0.92 | R | R | YES | A | A | ND | A |
| LOF | LOF | 1.0 | R | R | YES | R | ND | A | A |
| LOF | LOF | 1.0 | R | R | YES | A | ND | R | R |
| LOF | LOF | 1.1 | R | R | YES | A | ND | ND | A |
| LOF | LOF | 1.2 | R | R | YES | R | ND | ND | R |
| LOF | LOF | 2.6 | R | R | YES | R | R | R | R |
| LOF | LOF | 3.4 | R | R | YES | R | ND | R | R |
| LOF | LOF | 4.5 | R | R | YES | R | R | R | R |
| LOF | LOF | 6.6 | R | R | YES | R | R | ND | ND |
| POR | POR | 0.05 | A | A | NO | ND | A | ND | A |
| POR | POR | 0.1 | A | A | NO | ND | A | ND | A |
| POR | POR | 0.1 | A | A | NO | ND | ND | ND | ND |
| POR | POR | 0.33 | A | A | NO | ND | ND | ND | ND |
| POR | POR | 6.0 | R | R | YES | ND | A | ND | R |
| SLG | LOF | 0.4 | R | A | YES | A | ND | A | A |
| SLG | SLG | 0.63 | R | A | YES | A | A | A | R |
| SLG | SLG | 0.71 | R | A | YES | R | A | A | A |
| SLG | SLG | 0.83 | R | R | YES | R | R | A | R |
| SLG | LOF | 0.85 | R | R | YES | R | R | R | R |
| SLG | SLG | 0.85 | R | R | YES | R | R | R | R |
| SLG | LOF | 0.92 | R | R | YES | R | ND | A | R |

A - ACCEPTED; R - REJECTED; ND - NOT DETECTED

Figure 2 presents the number of discontinuities detected and correctly dispositioned by each of the inspection methods (including metallography). The figure shows that CAUT* detects and correctly dispositions more than MUT, Ir/AA, and CAUT. When strictly looking at the data from multiple inspectors, the figure shows that MUT detects and correctly dispositions more of the discontinuities than Ir/AA and CAUT. The percent of detected discontinuities correctly dispositioned by each nondestructive method is 79%, 80%, 71%, and 63%, respectively. Using Ir/AA as the standard method, the disposition reliabilities of the inspection methods may be considered comparable as there is approximately a 10% difference when comparing CAUT*, MUT, and CAUT to Ir/AA. It is expected that the disposition reliability of CAUT will increase to that of CAUT* as the experience level of the CAUT inspectors increases.

Table 2 - Rejectable discontinuities as identified by metallography and dispositioned by NDE

| | | MET | NDE INSPECTION TECHNIQUE USED: CAUT* | MUT | CAUT | Ir/AA |
|---|---|---|---|---|---|---|
| DETECTED | PLANAR | 22 | 19 | 18 | 9 | 9 |
| | VOLUMETRIC | 8 | 8 | 7 | 7 | 6 |
| | TOTAL | 30 | 27 | 25 | 16 | 15 |
| CORRECTLY DISPOSITIONED | PLANAR | 22 | 14 | 14 | 5 | 7 |
| | VOLUMETRIC | 8 | 7 | 6 | 5 | 3 |
| | TOTAL | 30 | 21 | 20 | 10 | 10 |
| NOT DETECTED OR INCORRECTLY DISPOSITIONED | PLANAR | 0 | 8 | 8 | 17 | 15 |
| | VOLUMETRIC | 0 | 1 | 2 | 3 | 5 |
| | TOTAL | 0 | 9 | 10 | 20 | 20 |

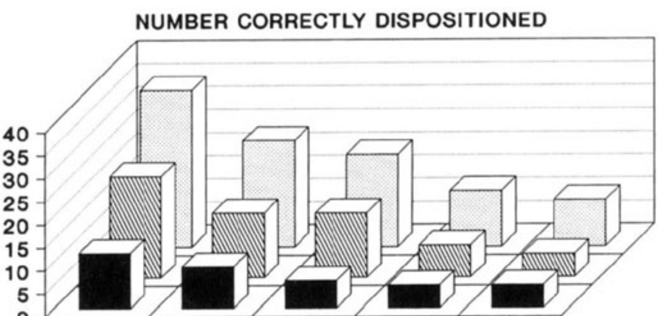



| | MET | CAUT• | MUT | Ir/AA | CAUT |
|---|---|---|---|---|---|
| DETECTION | 34 | 29 | 25 | 17 | 16 |
| CORRECT DISPOSITION | 34 | 23 | 20 | 12 | 10 |

INSPECTION METHOD

CORRECT DISPOSITION   DETECTION

Fig. 2. Number of discontinuities detected and correctly dispositioned.



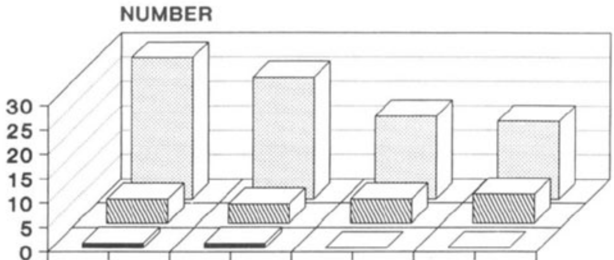

| | MET | CAUT• | MUT | Ir/AA | CAUT |
|---|---|---|---|---|---|
| TOTAL | 34 | 23 | 20 | 12 | 10 |
| PLANAR | 22 | 14 | 14 | 7 | 5 |
| VOLUMETRIC | 12 | 9 | 6 | 5 | 5 |

INSPECTION METHOD

VOLUMETRIC   PLANAR   TOTAL

CAUT• - EXPERIENCED OPERATOR

Fig. 3. Number of discontinuities correctly dispositioned.




| | CAUT• | MUT | Ir/AA | CAUT |
|---|---|---|---|---|
| TOTAL DETECTED | 29 | 25 | 17 | 16 |
| TYPE II ERROR | 5 | 4 | 5 | 6 |
| TYPE I ERROR | 1 | 1 | 0 | 0 |

INSPECTION METHOD

TYPE I ERROR    TYPE II ERROR
TOTAL DETECTED

Ho - DISCONTINUITY IS ACCEPTABLE
CAUT• - EXPERIENCED OPERATOR

Fig. 4. Number of discontinuities detected along with the number of types I and II errors made by each of the inspection methods.

The number of discontinuities correctly dispositioned is subdivided into planar and volumetric types and presented in Figure 3. This figure illustrates that CAUT* and MUT detect twice as many planar discontinuities as Ir/AA, and that CAUT* detects approximately twice as many volumetric discontinuities as Ir/AA.

Assuming that the results obtained by the experienced CAUT* operator will reflect the results obtained by any experienced operator, it follows from the data presented in Figures 2 and 3 that the use of computer assisted ultrasonics will increase the detection and disposition reliability for weld inspections.

Figure 4 presents the number of discontinuities detected as well as the number of types I and II errors made by each of the inspection methods. The null hypothesis is that a discontinuity is acceptable; therefore, type I errors occur when an acceptable discontinuity is rejected, and type II errors occur when a rejectable discontinuity is accepted. Type I errors result in increasing production costs, while type II errors result in not meeting the design criteria. This figure illustrates that a similar number of errors are made for each of the methods; however, taken as a percentage of the number of discontinuities detected, CAUT* and MUT make fewer errors than Ir/AA or CAUT (21%, 20%, 29%, and 38%, respectively). In terms of error, these results indicate that ultrasonic inspection is better as it detects more discontinuities with a smaller percentage of errors.

The difference in results between MUT and CAUT are believed to be due to differences in experience levels. The personnel who performed the manual UT inspections were shipyard inspectors with years of experience performing manual ultrasonics. The personnel who performed the computer assisted UT inspections were field UT inspectors and shipyard engineers (with less overall experience with UT); these people were trained and had used the P-scan system for only one week before inspecting the plates. Although the ultrasound is the same for MUT and CAUT, there are differences in the manner in which data is evaluated. The manual ultrasonic inspection is performed entirely in the field, with the inspector making decisions on the relevancy of indications (signals) and evaluating them on the spot. Conversely, for the computer assisted inspection, the inspector scans the weld and records the inspection data for later evaluation. Since the P-scan records amplitude and position information from all reflectors (including both real discontinuities and geometric reflectors) data interpretation involves a decision making process that does not benefit from having the ability to manipulate the ultrasonic signal. It has been shown that the use of computer assisted ultrasonics decreases amplitude and length variations of ultrasonic measurements [2]; because of this fact, it is believed that the detection rate and the disposition reliability for CAUT will increase to at least the level of MUT as the experience level of the inspectors increases. With proper training and experience, it is believed that the ability of CAUT to detect and correctly disposition discontinuities will increase to the level of the experienced CAUT or MUT operator.

## SUMMARY AND CONCLUSION

The objective of this work was to determine if welds may be ultrasonically inspected with detection and disposition reliability comparable to that currently obtained with radiography. Based on the results of this work it has been demonstrated that (a) computer assisted ultrasonics performed by an experienced operator resulted in the highest number of discontinuities detected and correctly dispositioned, (b) excluding the CAUT* data, manual ultrasonics had a higher detection rate for weld discontinuities than radiography or computer assisted ultrasonics, (c) overall, manual ultrasonics, radiography, and computer assisted ultrasonics (CAUT and CAUT*) have comparable disposition reliabilities, and (d) the error rate for detected discontinuities is similar for computer assisted ultrasonics performed by an experienced operator, manual ultrasonics, radiography and computer assisted ultrasonics. Thus, from a reliability standpoint, this work shows that ultrasonics is an acceptable alternative to radiography for weld inspection.

## REFERENCES

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2. R. DeNale and C. A. Lebowitz, in Proceedings of the 37th Defense Conference on Nondestructive Testing, pp 49-59 (1988).