

## THE USE OF FRACTURE MECHANICS METHODOLOGIES FOR NDT RESULTS EVALUATION AND COMPARISON

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### ABSTRACT

In the general frame of analyzing the interactions amongst the information from NDE and the methodologies to assess the integrity of a defective structure (such as Fracture Mechanics), the aim of the paper is to analyze and compare, in their structural integrity significance, NDE results from RRT trials to achieve assessments of capabilities and limitations.

A Structural Integrity / Fracture Mechanics approach for evaluating and comparing NDT results have been presented. Safety factors can be associated to flaws detected and characterized by inspections (estimated flaws) and to flaws actually present (reference flaws). The mismatch between safety factors associated to estimated flaws and safety factors associated to reference flaws can be used to assess capabilities and limitations of procedures and techniques in use for inspections.

As an example to show how the above procedure is applied and its potential as a method of data evaluation and comparison, the NDE results produced by the PISC activity have been considered. The method has proved capable of assessing capabilities and limitations of a single inspection and the influence on such capabilities and limitations of some equipment related parameters such as recording level and scan type and of some flaws related parameters such as flaws access and material.

### 1 INTRODUCTION

Flaws have a significant impact on the safety and structural integrity of operating process plant elements. The target of Non Destructive Techniques (NDT) is to detect, locate and size flaws in structural components. The knowledge of the defectiveness of a structure is a starting point for any structural integrity assessment. Hence there is a need to assess if NDT will be able to furnish the correct information on the defectiveness of a structure in regard to the presence, location, size and characteristics of flaws.

The general objective of assessing capabilities and limitations of procedures and techniques used for inspections can be achieved through experimental RRT (Round Robin Testing) trials such as PISC (Project for the Inspection of Steel Components) programmes in which inspections are performed on structures with known flaws.

RRT consists in the ultrasonic examination of the same flaws with the same type of procedure or with procedures based on the same technique on blocks or components. Each inspection determines location and sizes of flaws (Estimated Flaws). The inspected blocks or components are then examined with destructive techniques. For each block or component actually present flaws (Reference Flaws) are identified and sized.

RRT activity produces a set of data which must be organized in a specified format (e.g. BTB format in PISC) for analysis and evaluation. The mismatch between information obtained

through NDT and the effective status of the defective structure (reference flaws vs estimated flaws) has to be considered to make meaningful evaluations and comparisons of RRT results.

Two levels of analysis can be established to handle the RRT information.

The goal of first level analysis is correct measurement that is detection, correct location and sizing of flaws. An assessment of errors in flaw size or position have to be performed. Such assessment will result in evaluating the overall error and uncertainty in flaw size and location when these have been established with NDT. This level of analysis may be performed by comparing the estimated configuration (flaws estimated by inspections) and the reference configuration (actual or reference flaws) in the geometrical space in which they were identified (Evaluation of Results by "Comparison"). This type of processing RRT information, not only supplies an immediate image of the situation, but also forms the basis for any further elaboration.

The goal of a further level of analysis is to obtain correct information with regard mainly to detecting and characterizing flaws in terms of the consequences which can be correlated with the evaluated situation (Evaluation of Results by "Consequences"). The evaluation of NDT results may be performed in terms of their structural integrity significance since the main aim of Non Destructive Evaluations (NDE) for safety relevant structural components is to give reliable information about the defectiveness of the structures. The analysis may be performed by evaluating the consequences on safety factors of the differences between the estimated configurations achieved through different inspection procedures and techniques and the reference configuration.

Structural integrity reduction induced by the presence of flaws can be quantified using Fracture Mechanics for evaluating the safety factors of the structure in which the flaws are present. Such an approach allows the transfer of analyses and comparisons at the structural integrity level that is engineering significant and may identify trends which could not be pointed out otherwise.

In the general frame of analyzing the interactions amongst the information coming from NDE and the methodologies to assess the integrity of a defective structure (such as Fracture Mechanics), the aim of the paper is to analyze and compare, in their structural integrity significance, NDE results to achieve assessments of capabilities and limitations.

## 2 STRUCTURAL INTEGRITY / FRACTURE MECHANICS APPROACH

### 2.1 Structural Integrity Significance of flaws

The Structural Integrity / Fracture Mechanics approach allows for the consideration of the interactions between all elements which contribute to the safety and reliability of structural components (i.e. fitness for purpose). The presence and characteristics of relevant flaws interact with the mechanical properties of materials and the operating conditions to match the structural integrity requirements.

The RRT are characterized both by the flaws and by the components in which flaws are located. NDT results and destructive examinations define estimated and reference configuration in terms of flaws dimensions and locations. The block or component, where flaws are located, implies a definition of materials and operating conditions. The material used for manufacturing is set for every component. Mechanical properties matching Design Codes and technical literature can be adopted. A stress condition suitable to describe correctly the operating conditions of the component has to be assumed. Design Codes and engineering procedures or practices give the rules to identify representative stress states for each component and operating conditions.

As a procedure to evaluate the structural integrity reduction induced by flaws in defective elements, the one developed by CEGB "Assessment of Integrity of Structures containing Defects" and known as R6 may be considered as significantly usable due to its versatility. This procedure has been substantially incorporated into the BSI PD 6493: 1991, "Guidance on Methods for assessing the acceptability of Flaws in Fusion Welded Structures".

The R6 / PD 6493 procedure considers brittle fracture together with plastic collapse mechanisms. The operational conditions of a defective structure are represented in terms of two adimensional parameters  $L_T$  and  $K_T$  which identify the conditions of the structure being considered against the plastic collapse and brittle fracture respectively. The  $L_T$  parameter is set by the ratio

between the applied and the limit load; the  $K_T$  parameter is set by the ratio between the values of the applied and of the critical stress intensity factor  $K$ . Any limit condition, from the brittle fracture to the plastic collapse are continuously described by a curve, the Failure Assessment Line (FAL).

R6 procedure allows the evaluation of the Reserve Factor (RF) in terms of applied load for a given condition. Reserve Factor is defined through the ratio between the load corresponding to limit conditions and the actual applied load. Reserve Factor can be seen as an estimation of the structural integrity reduction induced by the presence of flaws.

Through the application of procedure R6 / PD 6493 Reserve Factors can be associated to flaws detected and characterized by inspections (estimated flaws) and to flaws actually present (reference flaws). The mismatch between safety factors associated to estimated flaws and safety factors associated to reference flaws can be used to assess capabilities and limitations of procedures and techniques in use for inspections.

Handling of RF and indices related to their mismatches may be a valid tool to solve the two following statements concerning NDE.

On the one hand there is the need to know if a single inspection would be capable of producing correct information to be used for structural integrity assessments, i.e., if the single inspection would provide the information in terms of detection, location and sizing of relevant flaws such to achieve evaluations of structural integrity reduction as close as possible to the actual (the reduction of structural integrity due to the reference flaws).

On the other hand there is the need to assess, in its structural integrity significance, the influence on NDE results of parameters related to the equipment, such as recording level, scan type, sensors and sensor combinations, and to flaw characteristics such as flaw access and material (wrought, weld, ferritic, austenitic).

## 2.2 Inspection Performance

A definition of Inspection Performance, so as to allow inspection capability in damage identification, can be stated to enhance discrepancies between estimated and actual structural integrities .

The Inspection Performance can be quantified by associating suitable quality indices for each detection made or missed and for each false call. A Penalty Index can be defined and evaluated by means a quadratic Penalty Function. The Penalty Index due to not detections can be assumed as a function of the relevance of the non-detected flaw and hence may be assumed as proportional to the squared reciprocal of the reference non-detected flaw's RF. The Penalty Index due to underestimations or overestimations of structural integrity significance of the reference flaws may be assumed as proportional to the squared ratio of the difference between the estimated and the reference flaws RFs and the reference flaw's RF. The Penalty Index due to false calls can be assumed as a function of the relevance of fictitious flaws and hence may be assumed as proportional to the squared reciprocal of the false call's RF.

Different weights, in the computing of Penalty Indices, may be attributed to non-detections, underestimations or overestimations of structural integrity significance of the flaws and false calls such as to favour safety considerations, economic considerations or technical considerations.

By summing up the Penalty Indices associated with each of the detections made or missed and with each of the false calls, Total Penalty may be obtained. The range of the Total Penalty can be normalized having defined the minimum and maximum levels. The minimum and maximum levels have to depend only on the inspected component and on its actual flaws. Such a method makes it possible to achieve comparisons amongst results from different components or different RRT trials. Hence it can be assumed that the minimum penalty corresponds to detection, exact location and sizing of all flaws; the maximum penalty corresponds to non-detection of any flaw. The Performance may be obtained as the complement to 1 of the normalized Total Penalty.

Performances can be broken down into Detection, Evaluation and False Call components whose combination gives the Overall Performance. Detection Performance can be obtained by considering only the penalties due to the non-detected flaws; Evaluation Performance can be obtained by considering only the penalties due to both missed flaws and estimations of actual flaws; False Call Performance can be obtained by considering only the penalties due to false calls.

The inspection performances can show, if considered one at a time, the capabilities of a single inspection in structural integrity identification allowing ranking and comparisons and, if considered as a whole, the level of difficulty of inspection of the component being considered.

### 2.3 Influence of Inspection Parameters

Having set the parameters being considered, their possible levels (e.g. scan type: manual and automatic; recording level: 50% DAC, 10-25% DAC and just above noise) have to be chosen. A Structural Integrity Response may be defined and used to assess, in their structural integrity significance, the influences of such parameters on NDE results.

The Structural Integrity Response can be quantified by defining a suitable Mismatch Function which provides values associating quality indices for each detection made or missed and for each false call.

The Mismatch Function may be stated as the difference between the reciprocal of the estimated and reference flaws RF. Underestimations of the structural integrity induced by the actual flaws allow negative values of the Mismatch Function while positive values correspond to overestimations. Non-detections and false calls can be considered as limit cases in which the estimated and the reference flaws do not exist. In such cases the reciprocal of the RFs of the estimated and the reference flaws are null. The Mismatch Function reduces to the reciprocal of the reference flaw's RF in the case of not detections while in the case of false calls it reduces to the reciprocal of the estimated flaw's RF.

The Structural Integrity Response is described through a stepwise function of the component or block defectiveness. False calls can be seen altogether and related to the not defective part of the structure. For each flaw, the Structural Integrity Response can be defined through the ratio of the Mismatch Function values and the maximum value corresponding to the not detection of the flaw. The false calls Structural Integrity Response can be stated by the ratio of the sum of Mismatch Function values due to false calls and the sum of Mismatch Function values due to not detection of all flaws. Maximum overestimations correspond to 1 and maximum underestimation (i.e. non-detections) to -1 for the Structural Integrity Response. The optimum Structural Integrity Response is given by the zero line.

The Structural Integrity Response have to be computed for each level of the inspection parameters. It shows the discrepancies with respect to the optimum response for each of the flaws and for the non defective part of the structure (false calls behaviour).

The Structural Integrity Responses may be synthesized through performance definitions. Trends of such performances may bring out useful and interesting considerations about the different influences of inspection parameters. Performances may be obtained using the modulus of the Mismatch Function values as penalty indices. Summing up the penalty indices, a total penalty may be obtained. Maximum and minimum levels of total penalty correspond respectively to detection, exact location and sizing of all flaws and to non-detection of any flaws. In this way, as in 2.2, the minimum and maximum levels depend only on the inspected component and on its actual flaws. Hence comparisons amongst results from different components or RRT trials are allowed. The performance may be obtained as the complement to 1 of normalized total penalty.

The performances for each level of the inspection parameters can be calculated. Plotting the performance values with respect to the levels of the inspection parameters, trends can be obtained. Performance trends show the influence, in structural integrity significance terms, of the levels of the inspection parameters on NDE results.

Detection, Evaluation, False Calls and Overall Performances can be calculated.

## 3 EXAMPLE OF APPLICATION TO PISC III RRT

As an example to show how the above procedure is applied and its potential as a method of data evaluation and comparison, the NDE results produced by the PISC activity were considered.

PISC III Action 3 Assembly No. 24, nozzle and safe-end of a BWR pressure vessel, was selected (Fig. 1). Estimated and reference flaws in BTB format were used. The materials used in manufacturing were well identified. Mechanical properties matching Design Codes and technical

literature were adopted. ASME Sect. III NB-3600 piping design rules were used to identify a representative stress state for the safe-end. Level A+B operating conditions and the design temperature ( $T=350^{\circ}\text{C}$ ) were chosen for setting the design limit stresses.

Fig. 2 presents the results of the performance evaluations achieved from the inspections performed on Assembly No. 24. Each inspection was characterized by an Overall Performance (OP) value. OP values determine whether a single inspection is capable of correctly evaluating the defectiveness of the Assembly No. 24. It is to be noted that although there are high performance inspection procedures, there is much variability overall.

Fig. 3 reports the Structural Integrity Response achieved by considering all those inspections performed with procedures recording indications just above the noise level. The Structural Integrity Response shows the behaviour of the procedures recording just above noise level on the Assembly No. 24 in terms of their overall capability to detect and correctly evaluate (locate and size) the actual flaws and of their false call rate.

Figs. 4 and 5 present respectively the influence on NDE results of the recording level, defining the sensitivity, and scan type parameters. Performance trends are reported in terms of Flaw Evaluation Performance (EP) and False Calls Performance (FCP). It is to be noted (Fig. 4) that a decrease in recording level provides a better Evaluation Performance, i.e. a better capability to detect and correctly evaluate (locate and size) the actual flaws, but produce an increase in the false call rate and then a decrease in False Call Performance. The Flaw Evaluation Performance seems to be related to sensitivity, with the noise level procedures performing better as a group than the 10-25% DAC procedures, which are in turn better than the 50% DAC procedures. False calls seem to be related to sensitivity too since their number and their structural integrity significance decrease by increasing the recording level.

Referring to Fig. 5, one can state that the automated procedures as a group appear to produce slightly better evaluations of actual flaws (higher Evaluation Performance) than manual procedures while, on the other hand, manual procedures as a group appear to produce less false calls (higher False Call Performance) than automated procedures.

Fig 6 presents both the effect of flaws access and material and the effect of recording level on the NDE capability to detect, locate and size the flaws through the EP trends. In the same way Fig. 7 presents the effects of flaws access and material and the effects of scan type on the EP trends. The improved behaviour in evaluating (detecting, locating and sizing) the flaws actually present in the assembly from the procedures using automatic scan and lower recording levels is more evident for flaws with uneasy access and for flaws in weld material. The importance of interfaces between wrought (transparent structure) and weld or buttering material is well illustrated by the performance in detection and evaluation of flaws in the weld and in the ferritic or wrought steel (Fig. 6, 7).

Analysis considering different mechanical properties and operating conditions matching realistic and technically sound situations for the component being considered were performed. Results of such analysis have shown that the reported trends and the above considerations are not affected.

#### 4 CONCLUDING REMARKS

Inspection techniques are or will soon be able to furnish in a reliable way the information needed for the structural integrity assessments with regard to the presence, location and size of flaws. Such information is relevant to structural integrity assessments and thus to plant life management.

The Structural Integrity / Fracture Mechanics approach, since using structural integrity related parameters, gives an engineering significant meaning to the evaluation of NDE results provided by RRT. The above results have shown the capability of the approach for evaluating and presenting the NDE results produced by RRT trials.

The method has proved capable of assessing capabilities and limitations of a single inspection, of enhancing the inspection results ranking and of providing a global view of the component's inspection complexity. The effectiveness of a single inspection depends on the way in which a performance demonstration is used. The Inspection Performance, as defined in the present paper, can be used to evaluate the results of performance demonstration exercises.

The influence of equipment related parameters and of flaws related parameters can be assessed in their structural integrity significance. Parametric analysis is a critically important engineering tool that can be used to improve the inspection performances and the capabilities of the procedures and techniques for the considered structural integrity / damage detection and evaluation. The Structural Integrity / Fracture Mechanics approach can be applied to assess which equipment related and flaws related parameters affect the information provided by NDE for that which concerns the defectiveness of a structure in terms of their consequences on structural integrity and thus on safety and reliability. The inspection procedures and techniques may be optimized by determining the levels of the important factors (e.g. the equipment related parameters such as recording level and scan type) that leads to the best possible response, i.e. to the correct information on the status of a structure and thus to a correct assessment of the structural integrity. The presented method, working in structural integrity terms, can then be a valid tool to perform such optimizations with the obvious limitation of the NDE techniques themselves which are suitable for certain categories or extend only of expected or unexpected material damage due to service.

As a further feature, the method allows analysis and comparisons amongst data produced by inspections on different blocks or components of the same RRT or provided by different RRT trials.

#### ACKNOWLEDGEMENT

This work was executed under CEC, JRC Contracts No. 43-91-06 ED ISP I and No. 4934-92-08 ED ISP I.

#### REFERENCES

- ASME, 1990, *Boiler and Pressure Vessel Code*, Sections III and XI, American Society of Mechanical Engineer.
- BSI, 1991, *Guidance on Methods for Assessing the Acceptability of Flaws in Fusion Welded Structures*, BSI PD 6493: 1991.
- Crutzen S., Jehenson P., Nichols R.W., Mc Donald N., 1989, *The major results of the PISC II RRT*, Nucl. Engrg. & Des., 115 (1989).
- Crutzen S., Nichols R.W., Kussmaul K., Yagawa G., 1989, *Developments in Fracture Mechanics and Non Destructive Examinations*, SMiRT 10 div. G Pricipal Div. Lecture.
- Crutzen S., 1993, *Evaluation Procedures of the PISC III RRT Results*, SMiRT 12 paper G03/4.
- Crutzen S., Jehenson P., Herkenrath H., Nichols R.W., Strosnider J., 1991, *The PISC III Programme - A Status Report*, SMiRT 11 div. G.
- PISC III, 1992, *Evaluation of the Inspection Results of the PISC III Assembly No. 24*, PISC III Rep. No. 24 to be publ. as EUR Rep..
- Milne I. et al, 1986, *Assessment of the Integrity of Structures Containing Defects*. R/H/R6 Rev. 3, CEGB. Also in Int. J. Pres. Ves. & Piping 32 (1988) 1-4.
- Milne I. et al, 1987, *Background to and Validation of CEGB Report R/H/R6 Rev.3*. R/H/R6 Rev. 3 Validation, CEGB. Also in Int. J. Pres. Ves. & Piping 32 (1988) 1-4.
- Reale S., Tognarelli L., 1993, *Evaluation of PISC Results by means of Fracture Mechanics Methods*, PISC DOC (93), Draft 1993.

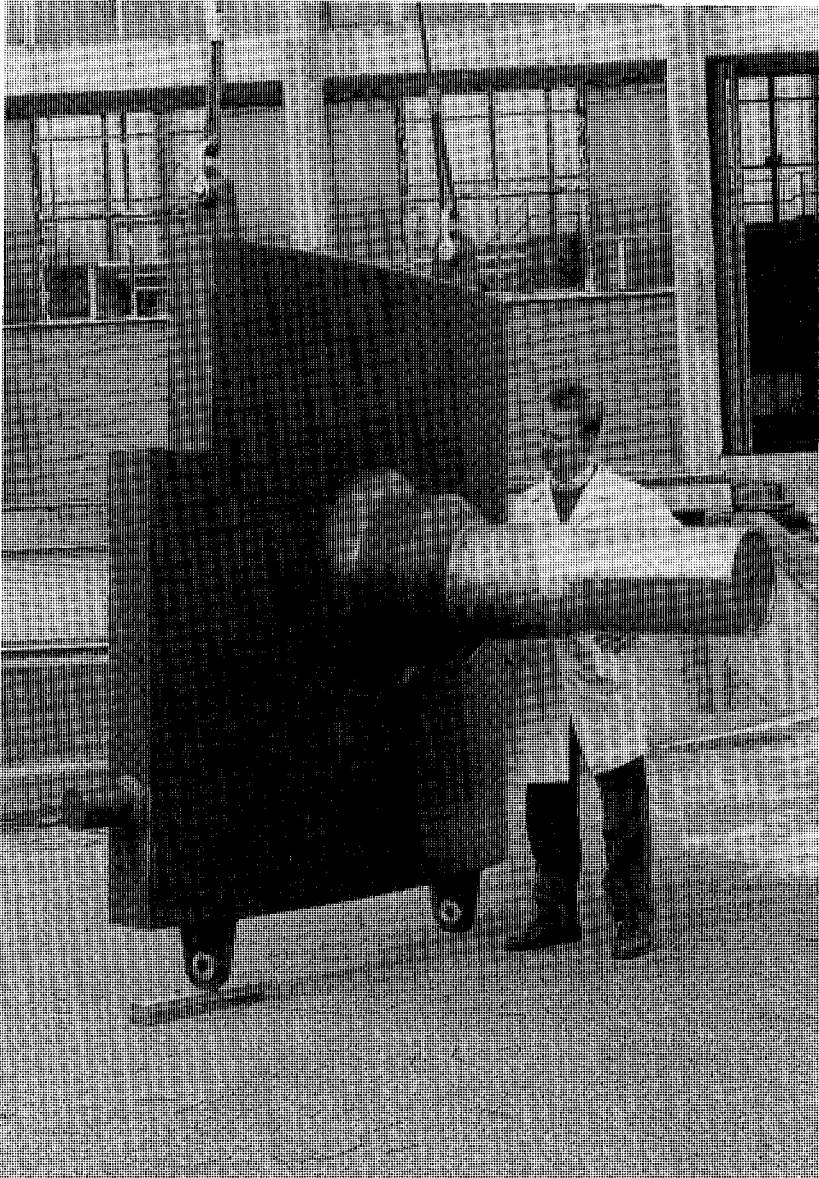


Fig. 1 PISC III Assembly No. 24

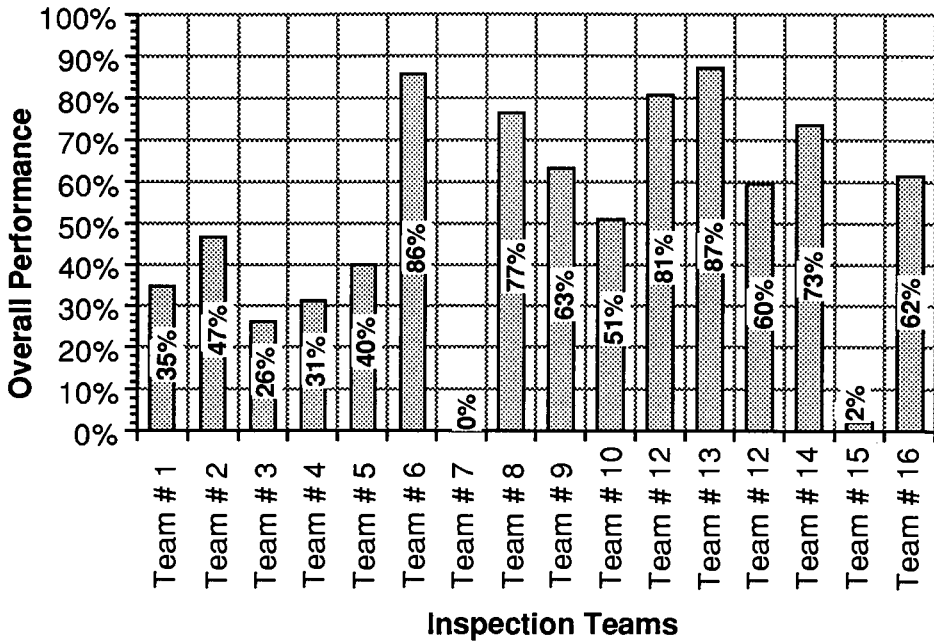


Fig. 2 PISC III Assembly No. 24 Inspection Performances

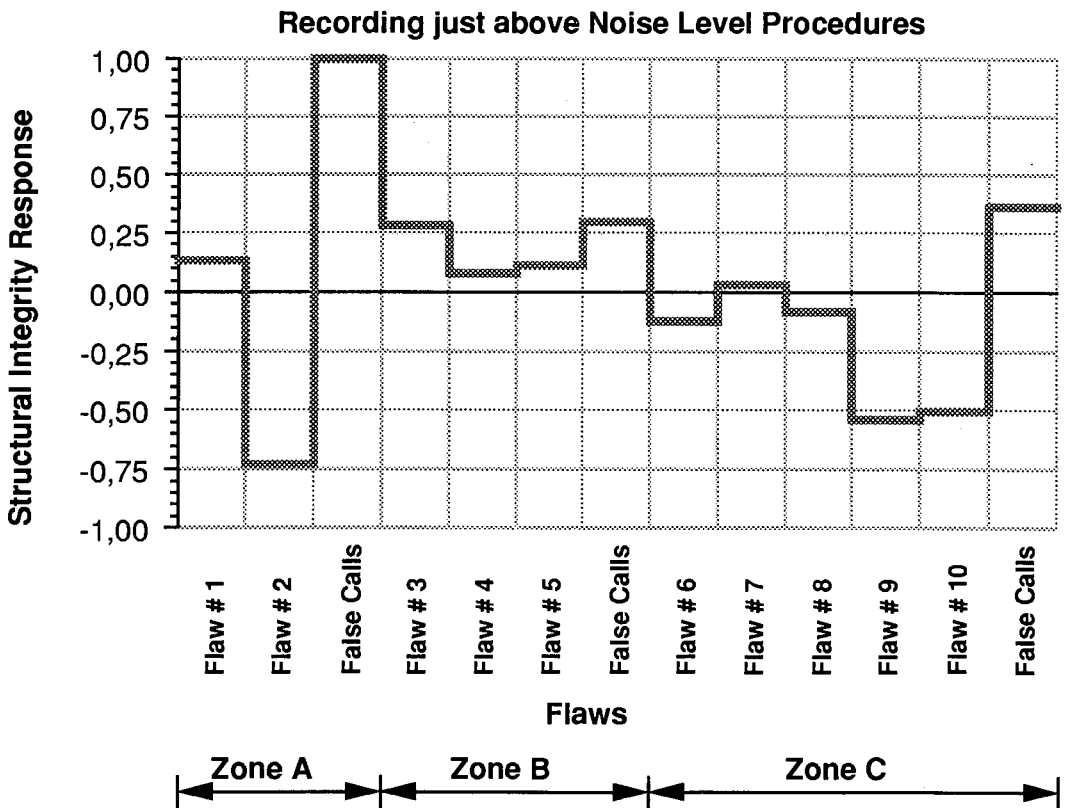


Fig. 3 Structural Integrity Response of procedures recording just above noise level in PISC III Assembly No. 24

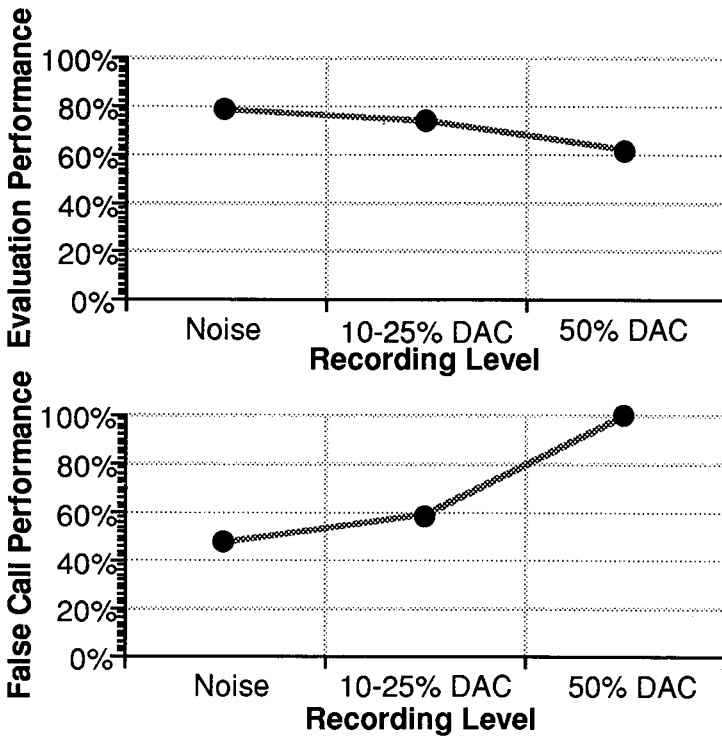


Fig. 4 Influence of recording level on NDE results of PISC III Assembly No. 24

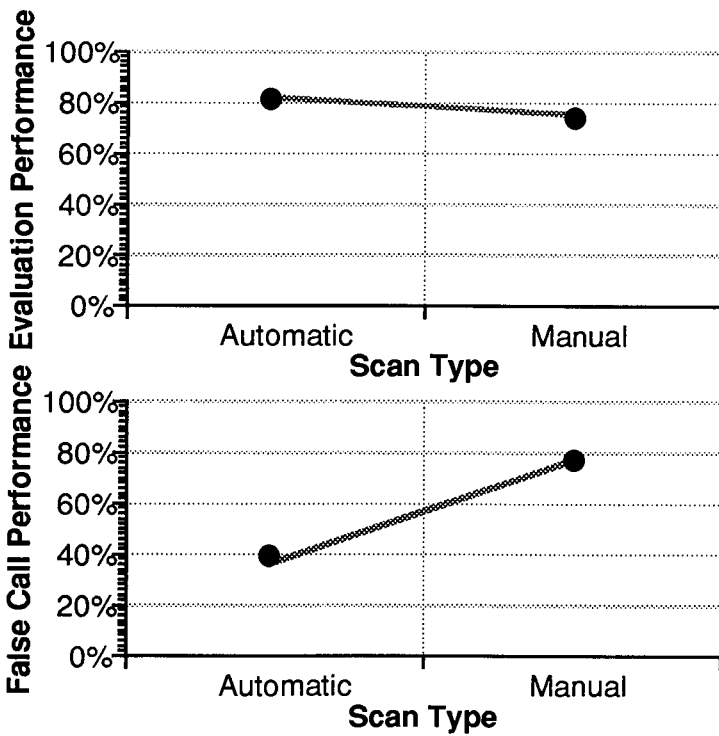


Fig. 5 Influence of scan type on NDE results of PISC III Assembly No. 24

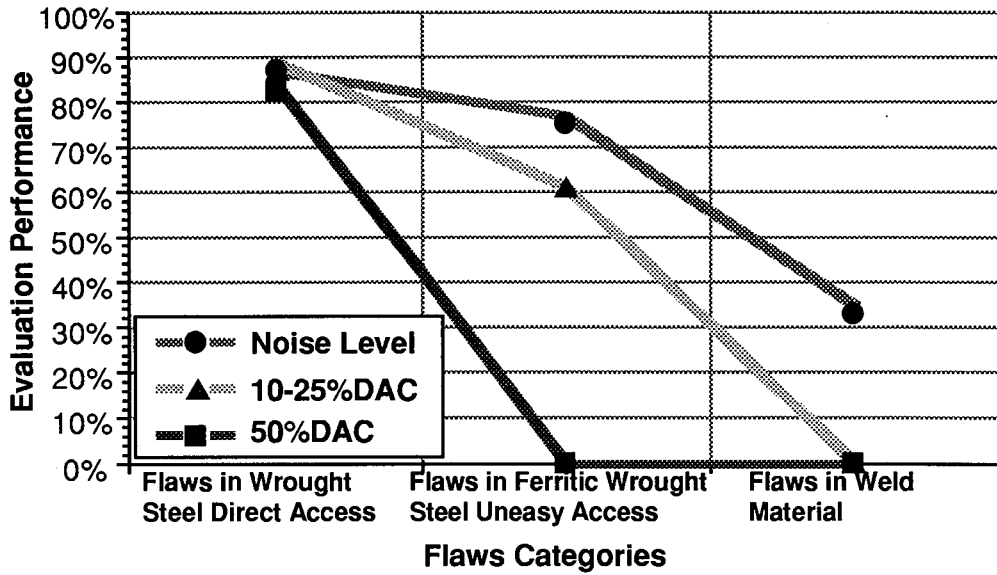


Fig. 6 Influence of recording level and of flaws access and material on NDE results of PISC III Assembly No. 24

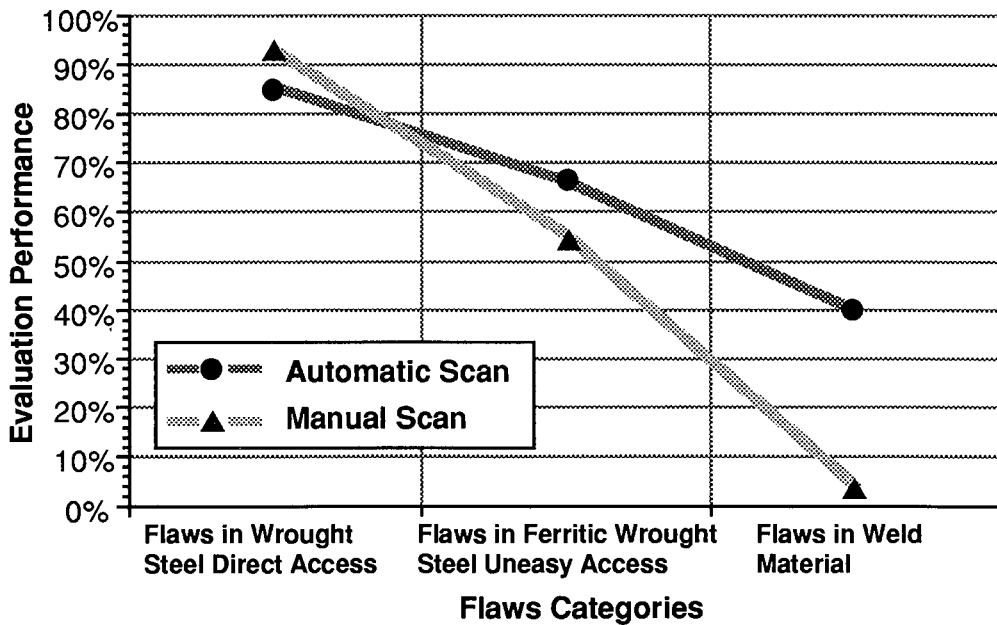


Fig. 7 Influence of scan type and of flaws access and material on NDE results of PISC III Assembly No. 24