The major results of the PISC II Round Robin test

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1 INTRODUCTION

Non Destructive Testing (NDT) forms part of the in-service inspection (ISI) of a reactor pressure vessel (RPV) and its associated pressure circuit, and the results of the NDT are used in conjunction with fracture mechanics or as part of a code-defined treatment to assess the significance of flaws. Detection, location and sizing of crack like defects play an important role in helping to establish the integrity of this reactor steel structures.
There is a need to have information on the accuracy of NDT for sizing and locating flaws and on the reliability with which flaws are detected. It is in providing an experimentally determined basis for such knowledge that trials such as those done in the PISC programmes have importance.

One of the first trials to give quantitative evidence on the ability of ultrasonic testing (UT) to find and size crack like flaws was the PISC I Round Robin exercise which mainly was concerned with normal UT of welded, thick steel pressure vessel plates containing deliberately introduced flaws (1)(2). The procedures were based on those of ASME Section XI (1974). The results showed somewhat poor performance for such procedures, but some aspects of these PISC I tests were not regarded as definitive, owing to the limitations of the project and the impossibility of separating overlapping defects. In addition the results of "alternative procedures" which supplemented the ASME type procedure indicated optimistic trends which needed further investigation.

There was clearly a need to collect more data in order to obtain better-defined results and broader conclusions. There was also a gap in the PISC-I results for flaws of intermediate size.
Thus a second set of round robin trials was necessary. It was also considered necessary to add separate studies on certain

parameters which influence flaws detection and sizing, to assist both in understanding the dispersion in the RRT results and in assessing the performance of the specific techniques applied.
These factors led to the PISC-II programme being initiated under the aegis of the Nuclear Energy Agency (OECD-NEA) and the Commission of the European Communities (CEC) (1)(3). This programme was included in the Direct Action Programme of the Ispra Establishment. As a result, resources for technical management and execution of the project were made available from the budget of the Commission of the European Communitites. The Ispra Establishment filled the function of Operating Agent for the programme which was guided by a Managing Group made up of representatives of the fifteen participating countries working to OECD rules of procedures and with an OECD-NEA Secretariat. The participating countries provided resources in kind in the form of test plates, inspection teams and expertise (Table 1).

2 THE OBJECTIVES AND THERMS OF REFERENCE OF PISC II

2.1 The objectives of the PISC-II programme were :

- to evaluate the effectiveness of NDT techniques either in use or being developed for the inspection of reactor pressure vessel components, with regard mainly to detecting and characterising service-induced flaws.
- to identify techniques for acceptance tests, pre-service inspection (PSI) and in-service inspection (ISI) which could be generally accepted, and
- to bring the conclusions of the programme to the attention of the Code, Standard and Regulatory Bodies concerned with ISI.

In planning the programme, emphasis was put on examining ISI techniques and procedures, and on the second of the three objectives. It was thus hoped to have a majority of automatic scanning inspection procedures represented in the round robin test. At the end, the PISC II programme included more manual procedures that had been expected.

2.2 The Round Robin Tests

The details of this programme have been given in the full reports of the PISC II programme (3). The round robin tests on four main test assemblies or "plates" (figure 1) extended over two and a half years, and ended with all the plates being returned to Ispra in September 1984. It involved 50 teams in 15 countries. The four plates contained a total of 120 defects; most of these defects were simulations of service defects.
The analysis of the results, after destructive examination of the assemblies, led to general trends given as conclusions.

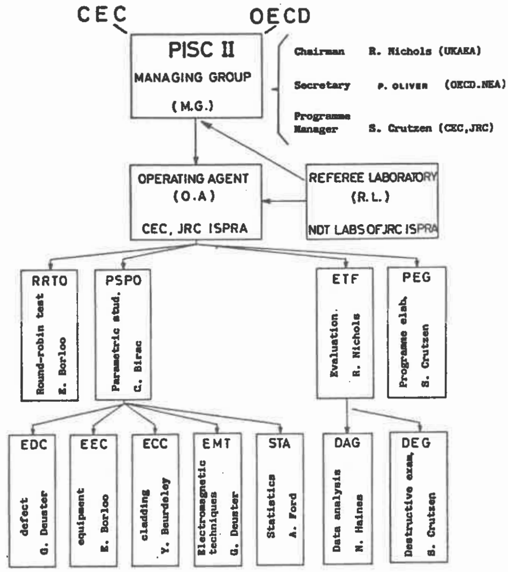
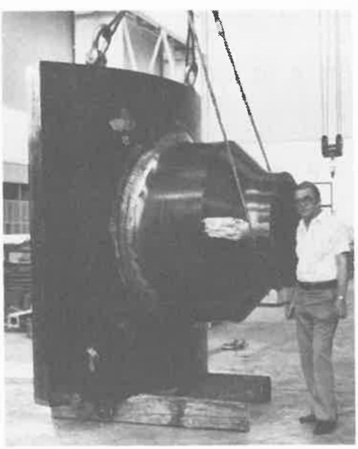
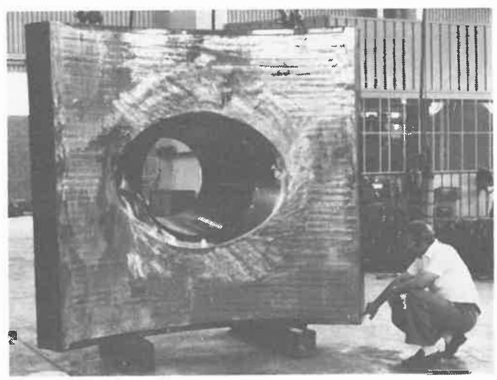


Table 1 : Organization scheme of the PISC II programme management.





PISC II Plate No. 3

PISC II Plate No. 9

Weldment of PISC II Plate No. 9 after destructive examination.

Figure 1 : PISC II Plates No. 3 (PWR nozzle) and No. 9 (BWR nozzle).

2.3 Parametric Studies

The PISC II programme also included parametric studies which were designed to complement the round robin tests. The importance of several parameters had become evident during the PISC-I programme, and in fact seven groups of significant parameters were readily identified. Four of these seven groups were selected for study as an essential part of the PISC-II programme.

1. Defect position and geometry study (EDC)

The effect of defect position and characteristics had to be investigated to help in understanding the round robin results.

2. Equipment characteristics study (EEC)

This involved studying what effect different equipment characteristics had on the reliability of the NDT results.

3. Cladding study (ECC)

This study was intended to help in evaluating the round robin test results, in particular to explain inconsistencies and limitations attributable to the cladding.

4. Possible use of electromagnetic techniques study (EMT)

An enquiry and tests were also performed by the IZfP (Federal Republic of Germany) on the possible use of electromagnetic techniques for conducting non-destructive examinations.

3 MAJOR RESULTS OF THE PISC II PROGRAMME AND THEIR DISCUSSION

3.1 Overall performance

The PISC II reports have presented comparative results on the performance of a number of NDE procedures and techniques and on the resources required to use these. Together, these results can be used to provide an engineering value impact assessment of the relative resources necessary to achieve a given level of reliability using various NDE procedures. Specifically, results have been presented which compare the detection reliability, location and sizing accuracy of procedures and which reveal the inspection complexity, level of training and time required for a given examination. As an example, (figure 2) shows the average performance achieved on plate No. 3 (the realistic PWR nozzle-shell assembly) and the comparative resources expended using different procedures.

It appears that better performance was generally obtained with procedures which involved taking longer times for data acquisition and which involved the use of highly qualified people for the evaluation of the recorded signals. The first aspect (data acquisition) points to the need to the development of scanners and data acquisition systems so that they will work within a scanning time which is acceptable for industry. The importance of the use of highly qualified staff could diminish in the future as modelling techniques and parametric studies develop expert diagnostic systems to help technicians.

3.2 Defect Detection and Rejection

Decreasing the "cut-off" (reporting) level for an ASME type examination from 50% DAC to 20% DAC increases the detection rate and improves the correct rejection rate of rejectable defects (figure 3).
A number of points may be raised in discussion of this important result. The use of 20% DAC rather than 50% may for some industrial applications cause loss of time : structures manufactured and controlled on the basis of a 50% DAC procedure will show many indications if controlled later at 20% DAC. The use of high sensitivity which appears necessary for effective performance may then have to be limited to those areas which are important from a structural integrity point of view (e.g. the first 25 mm near to the clad surface). The possible use of 10% DAC (or even lower) cut-off may be possible and beneficial with procedures which use elaborate data evaluation to reduce the number of resulting calls and also could be of interest for fabrication controls where all manufacturing defects have to be detected in order to permit clean ISI at 20% DAC later. ISI is supposed to detect service induced defects and to control them.

3.3 Importance of supplementary probes

Procedures in the spirit of ASME Section XI appear to perform better if a 70^{o} longitudinal waves angle probe is added either in the simple echo technique or with dual beam, or both.
Figure 4 on plate No. 2 shows the importance of supplementary techniques : an ASME procedure at 35% DAC complemented with 70^{o} angle probes and tandem probes matches the detection rate achieved with the 10 per cent DAC procedure. Detection of near surface cracks is very important from a structural integrity viewpoint. The PISC II RRT shows that the major contribution to detection of these defects is given by the 70^{o} SEL probe.

3.4 High performance of special procedures

The so called special procedures that combine standard techniques and advanced techniques for sizing (but often also for detection, e.g. TOFD) obtain nearly perfect results as shown on figure 5. Such procedures, generally proposed for ISI are only just beginning to be industrially used.
These procedures were conducted with mechanized scanners and, in the stage of development in which they were used on PISC II, required a long time for data acquisition. In most cases several weeks were required for the data handling and presentation of results of these procedures applied on the PISC II assemblies; moreover, the evaluation team was of high scientific level. One team, however, performing ISI routinely up to 20 times a year,

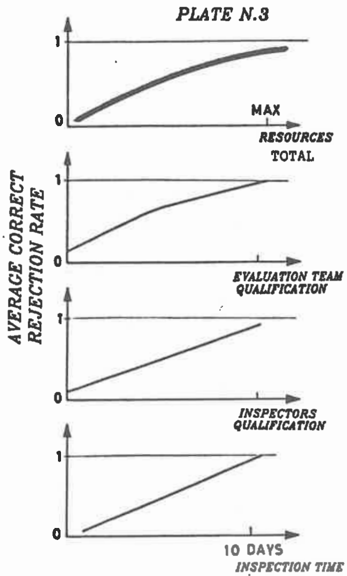


Figure 2 : Performance (detection and acceptable evaluation of re-jectable defects) of NDT procedures as a function of the resources available to the ins-pection team (ave-rage values over 40 teams).

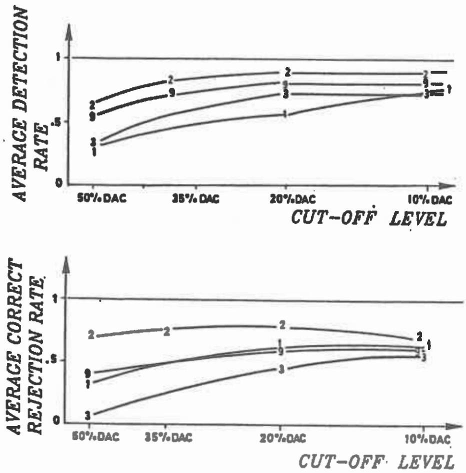


Figure 3 : Detection rate and correct rejection rate (of rejecta-ble defects along ASME cri-teria) as a function of the recording level for ASME ty-pe procedures (all four PISC II assemblies).

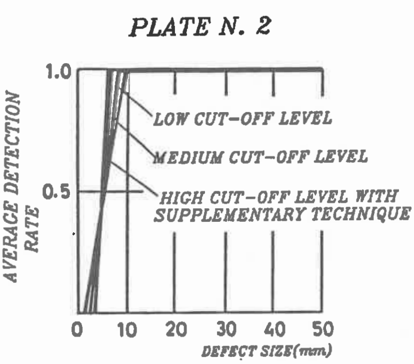


Figure 4 : Importance of supplementary techniques such as the 70° angle probes for near sur-face defects detection.

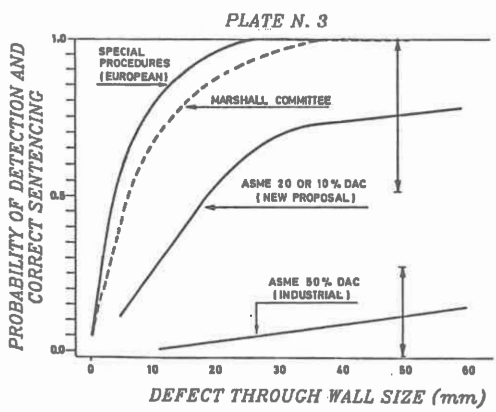


Figure 5 : High performance of "spe-cial procedures" compared with the LWRSG curve and ave-rage performance of ASME ty-pe procedures.

scanned the Nozzle Plate No. 3 in less than one hour and produced good inspection results rapidly.

3.5 Importance of the sizing uncertainity

Several teams declared an error band or uncertainity on the size of defects as evaluated with ultrasonic techniques, so trials were made using a tolerance on defect size as a parameter.

As shown on figure 6, all "special" full procedures achieved perfect rejection of rejectable defects when the reported defect sizes are increased by a tolerance addition of only 3 to 6 mm. The diagrams of figure 6 however shows that procedures in the spirit of ASME never reached perfect rejection : the upper limit of performance is equal to the detection rate of rejectable defects. Some advanced sizing techniques are shown to be able to reach 100% rejection of the rejectable defects which have been considered by these techniques.

3.6 Importance of defect position in the through thickness direction

Although detection does not seem to be too dependent on the defect position in the plate thickness, sizing quality is dependent on this parameter as shown on figure 7. Defects located deep in the wall thickness are, on average, oversized. The chance of undersizing defects is greater for those defects located near to the clad surface.

3.7 Importance of the defect size

Defect size appears to affect both detection and sizing of these defects :

1. On average, there is a lower detection performance for defects smaller than 10 mm in height. This observation has, however, to be considered further as a function of the defect characteristics.
2. The error on defect size is dependent on the size of the defects as shown on figure 7. The major chances for undersizing exist for defects of the critical size.

3.8 Importance of the defect charateristics

When considering defect characteristics such as the crack tip aspect and surface roughness it was possible to divide all defects in the PISC II assemblies into three categories :

A. smooth cracks with sharp crack edges (fatigue cracks);
B. rough cracks and cracks which were strongly modified during implantation and have unrealistic crack tip aspects;
C. volumetric defects (slags and porrosities).

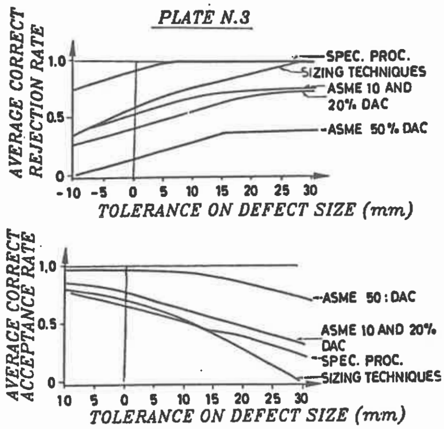
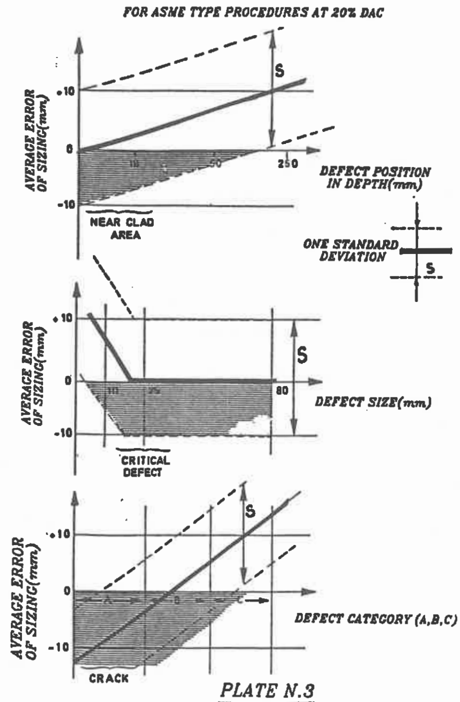


Figure 6 : Defect evaluation performance as a function of a sizing tolerance (or uncertainity) added to the declared size of the rejectable defects. (PISC II assembly No. 3 : PWR nozzle).



Legend : ═══ Condition for major chances of undersizing defects.

Figure 7 : Importance of defect parameters such as defect position, size, characteristics. Average error of sizing as a function of these parameters.

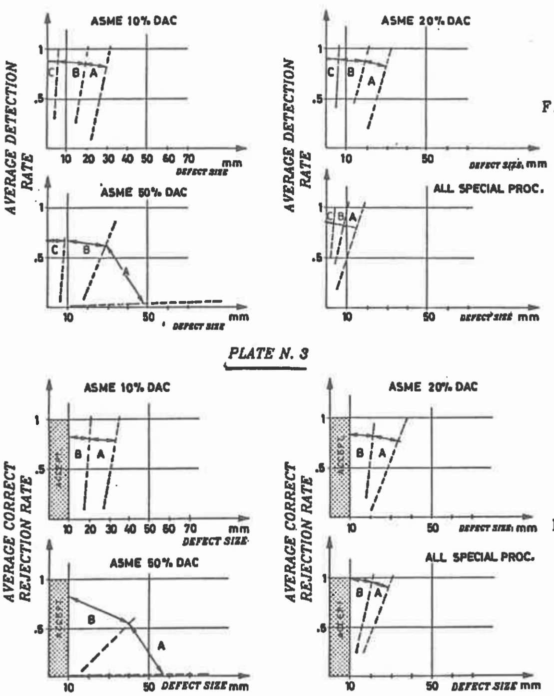


Figure 8 : Detection rate and correct rejection rate of rejectable defects as a function of :
- defect category (A,B,C),
- defect size (through thickness dimension),
- inspection procedure type.

Category A defects appear to be the most difficult ones in this context. It may therefore be concluded that such defects should be emphasised in validation exercises (figure 8). Such a plot appears to be valid for the results of all four PISC-II plates. This way of presenting the data also explains some results of the PISC-I and DDT exercises (4)(5).

3.9 Worst case

To summarize figure 7, the results indicate that the most difficult case is a category A defect of 25 mm or more in height near to the clad surface. Such a defect could be undersized.

3.10 Contribution of individual techniques to the performances of full procedures

Full procedures are made up of individual techniques which can be regarded as components. A major question is what is the individual contribution of each of these components to the overall performance of one full procedure.
In evaluating the results of techniques, parameters such as cut-off level, surface used for scanning, defect position, defect size and defect category have to be considered.

1. Contribution of techniques in general

The diagrams on figure 9 show the performances which were reached by individual techniques applied on three PISC II assemblies. The contribution of the 70^{o} angle probes for near surface defects is important compared to the performances of the 45^{o} and 60^{o} angle probes. 70^{o} angle probes are efficient, even when the general level of 50% DAC is used as cut-off level.

2. Influence of the scanning surface considered

For plate No. 3, correct rejection of defects by techniques at 45^{o} and 60^{o} is systematically lower when the clad surface is used for scanning. Such an influence is not so systematic on the other PISC II plates.
A conclusion of the PISC II RRT is that the cladding did not influence strongly the performances of techniques but it could, however, affect sizing.

3. Importance of defect size

For all three techniques when using the clad surface for scanning, the trend is that the largest defects are undersized. This confirms the global evaluation of results.

4. Importance of defect characteristics

As for full procedures, individual techniques show performances depending strongly on the defect characteristics.

5. Optimization of procedures

Using the data corresponding to individual techniques and combining all the recorded indications by groups of techniques, one

can constitute artificial procedures, e.g.:
- ASME at 20% DAC : 0^o, 45^o, 60^o angle probes;
- Complemented ASME at 20% DAC : 0^o,45^o,60^o,70^o (S,L or SEL) angle probes;
- Reduced ASME at 20% DAC : 45^o,70^o (S,L, or SEL) angle probes.

Figure 10 shows the performances of these artificially constituted procedures.

It is to be noted that the combination of the only two techniques (45^oS and 70^o SEL) reaches a performance comparable to the complemented ASME. More probes could higher the performance of few percent but would result in injustified rejects of acceptable defects (figure 10).

6. Complementarity of techniques

The complementary nature of the 45^o and 70^o techniques with one being effective on defects for which the other is less effective was clearly shown during the evaluation of results. A similar complementarity exists between the 60^o and 70^o techniques.

Tandem techniques do not appear to increase detection systematically when couples of techniques such as 45^o and 70^o or 60^o and 70^o are used.

TOFD alone is found in this work capable of doing most of the job and it is clear that a combination of techniques involving TOFD must reach high performances. This is in fact the case for procedures identified as "special procedures" results.

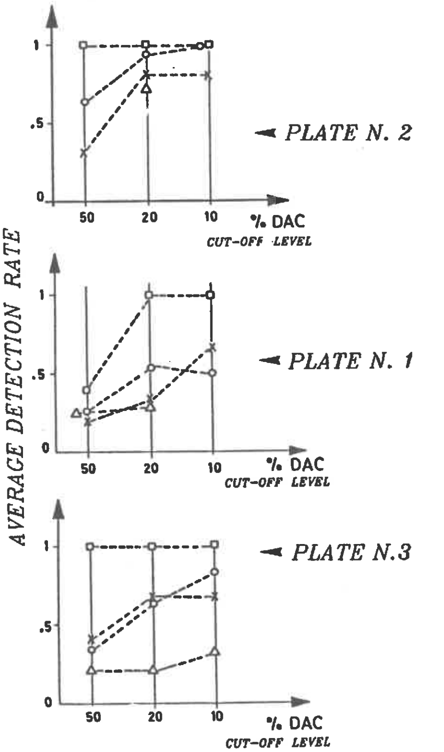
3.11 Dispersion of results

Over all teams and defects, a high dispersion of the results relating both to sizing and to location error occured (figure 11). In particular, dispersion of sizing and location accuracy in the defect length direction was much worse than in the defect height direction. Such dispersion must be noted when discussing the validity or efficiency of repairs and in assessing the significance of flaws.

3.12 Results of the Parametric studies

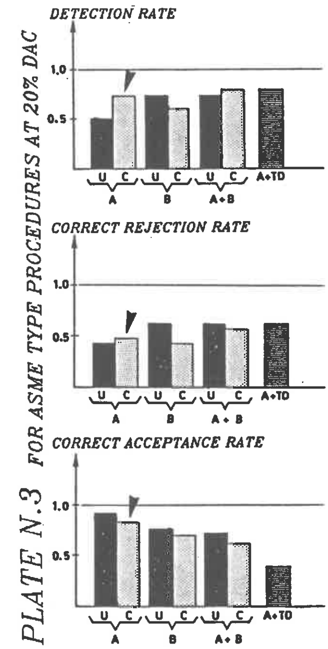
Parametric Studies under PISC II generally confirm or partially explain several results of the Round Robin Tests :
- limited defect detectability by particular techniques;
- sizing dispersion due to equipment characteristics; and
- influence of the clad surface on sizing accuracy.

The group of parametric studies producing the most important results is the one on the effect of defect characteristics on detection and sizing; these laboratory exercises are to be continued under the PISC III programme.



□ = 70 DEG.(S,L,SEL) FROM 0 TO 18 mm
X = 45 DEG. FROM CLAD SIDE
O = 60 DEG. FROM CLAD SIDE
△ = TANDEM FROM CLAD SIDE

Figure 9 : Performance of individual techniques as a function of the recording level.



<u>LEGEND</u>

U : INSPECTION FROM UNCLADE SIDE
C : INSPECTION FROM CLAD SIDE

ARTIFICIAL PROCEDURES :

A = 45 DEG + 70 DEG (FROM 0 TO 20 MM)
B = 0 DEG + 45 DEG + 60 DEG
A+B = 0 DEG + 45 DEG + 60 DEG + 70 DEG
A+TD = 45 DEG + 70 DEG + TANDEM

Figure 10 : Optimization of procedures : performance of procedures as a function of their constitutive individual techniques.

PLATE N.3

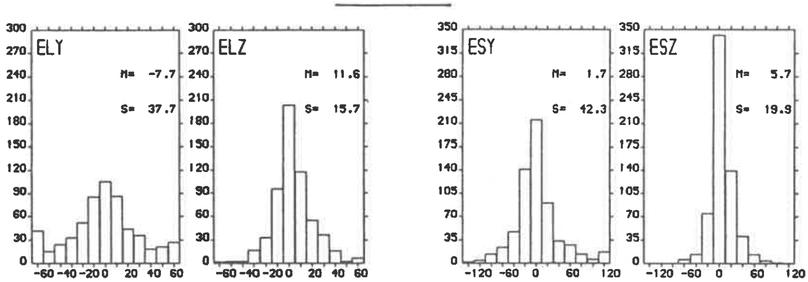


Figure 11 : Dispersion of location and sizing errors.
ELY, ELZ = error of location in the circumferential direction and through thickness direction.
ESY, ESZ = error in size int he circumferential direction and through thickness direction.

4 LIMITATION OF THE PISC II RRT RESULTS

Some aspects of the PISC II progamme may limit the applicability of the conclusions.

1. A substantial number of the PISC II tests were done manually whereas fully automated procedures are typical of ISI. Further work on the comparison between manual and mechanized scanning will be performed under PISC III on large size assemblies.

2. Most of the defects were artificial or artificially introduced and a validation of the results of PISC II is necessary on real defects and will be done in PISC III. However, comparisons of the ultrasonic responses from the artificial defects of category A with those from real fatigue cracks showed that these artificial defects were a good basis for test.

3. Some particular aspects of the plates have probably biased the results. For example there were many satellite defects near to the intended defects in plate No. 2.

4. The PISC II inspections were generally performed in laboratory rather than in real industrial conditions.

5 CONCLUSIONS

The results of the PISC II exercises provide information on key aspects of ISI procedures :

- detection and sizing performances;
- worst possible cases;
- qualification of inspection required.

Such results are relevant to aspects of the present widely used codes such as ASME, and can indicate where modifications or optimizations could be made so that higher average performances can be expected. The PISC II exercise also presents a very positive validation of several full procedures, some of which had shown positive trends in PISC I under "alternative techniques" and some of which involve combinations of standard and advanced techniques. Although, PISC II shows that satisfactory defect detection could easily be obtained, it emphasizes that sizing is far from ideal even when Advanced Sizing Techniques are used. Often, several advanced techniques for sizing produced perfect results for some defects but in some cases they failed. This is due to one or more of the following reasons:

- Scanners were often not adapted to the real situation.
- The results demonstrated too much contribution from the original "developer" or from highly skilled operating staff.
- Few real defects are generally available for validation of these techniques so that some teams, with experience mainly of geometrical and artificial defects, often did not believe the results shown by their own instrumentation.

Improved performance of ISI requires further work in three directions :

- Simple optimization of existing codes by making the right choice of the recording cut-off level and of the probes or techniques. Validation of these new procedures is necessary on realistic structures, containing relevant realistic defects.
- The industrial development of scanners for sizing techniques and experimental application of these techniques.
- The development of relevant mathematical models, together with their validation and parametric studies to create a bank of information to be used by expert systems for the on-line analysis of signals.

Until they are available, an emphasis on the selection of scientifically and technically qualfied staff is essential.

PISC II introduced the concept of defect categories. In ISI, sharp, planar and smooth defects (category A) are of concern from a structural integrity viewpoint. Optimization of inspection procedures for detection of such defects has been indicated by the PISC II results. However, one important aspect has to be discussed : even if techniques are assembled for the detection (and possibly sizing) of category A defects, the procedure has to include an effective validation procedure. As shown on figure 8, setting up a system using the current calibration blocks which contain volumetric defects (family C on figure 8) will not provide any reliable detection of a fatigue crack (family A on figure 8). The current calibration block is valid to set the equipment but not to verify the performance of a procedure. It is however, perhaps not necessary to conceive complex blocks with real defects of all kinds. Artificial defects of category A in the simple PISC parametric study blocks are in fact being shown to be sufficient in many cases (4).

The results of PISC II also have learned lessons for those concerned with developing materials. The experience on Plate No. 1 confirms that already reported from other round robin trials that clean material, free from defects in the base material, is desirable if high levels of detection are required.

From a fracture mechanics viewpoint the most important information from PISC II perhaps relates to possible errors in size and location of defects. A conservative treatment of UT results should take note of these aspects.

PISC II aimed only at the evaluation of performance. Reliability aspects have also to be considered. Even in the case of a performant procedure, the periodic verification and validation of its performances will be necessary well into the future.

Finally it has to be noted that NDT is only one imput to integrity assessments and similar attention to that given to NDE in PISC II should be given to other activities such as Fracture Mechanics and Materials.

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