Round robin test programmes in the reliability of thick section ultrasonic inspections – State of the art report

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OECD Nuclear Energy Agency, 38 bd Suchet, F-75016 Paris, France
The NEA Committee on the Safety of Nuclear Installations (CSNI) is an international committee made up of scientists and engineers who have responsibilities for nuclear safety research and nuclear licensing. The Committee was set up in 1973 to develop and co-ordinate the Nuclear Energy Agency’s work in nuclear safety matters, replacing the former Committee on Reactor Safety Technology (CREST) with its more limited scope.

The Committee’s purpose is to foster international co-operation in nuclear safety amongst the OECD Member countries. This is done in a number of ways. Full use is made of the traditional methods of co-operation, such as information exchanges, establishment of working groups, and organisation of conferences. Some of these arrangements are of immediate benefit to Member countries, for example, by enriching the data base available to national regulatory authorities and to the scientific community at large. Other questions may be taken up by the Committee itself with the aim of achieving an international consensus wherever possible. The traditional approach to co-operation is increasingly being reinforced by the creation of co-operative (international) research projects, such as PISC and LOFT, and by a novel form of collaboration known as the international standard problem exercise, for testing the performance of computer codes, test methods, etc. used in safety assessments. These exercises are now being conducted in most sectors of the nuclear safety programme.

The greater part of the CSNI co-operative programme is concerned with safety technology for water reactors. The principal areas covered are operating experience and the human factor, reactor system response during abnormal transients, various aspects of primary circuit integrity, the phenomenology of radioactive releases in reactor accidents, and risk assessment. The Committee also studies the safety of the fuel cycle, conducts periodic surveys of reactor safety research programmes and operates an international mechanism for exchanging reports on power plant incidents.

The Committee has set up a Sub-Committee on Licensing which examines a variety of nuclear regulatory problems, provides a forum for the free discussion of licensing questions and reviews the regulatory impact of the conclusions reached by CSNI.

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IN THE RELIABILITY OF THICK SECTION ULTRASONIC INSPECTIONS

by B Watkins

1. Introduction

Non destructive testing (NDT) plays an important role in the integrity arguments in any engineering structure. It is particularly important in components where loading factors can lead to disruptive failure. For some structures it can be argued that leakage of the pressurising media will occur before disruptive failure. This concept of 'leak before break' is based on the fracture mechanics argument that the critical flaw height in the through thickness direction always exceeds the vessel thickness. In these circumstances non destructive examination (NDE) should be aimed at detecting leakage and the length of any incipient flaw. On the other hand, if the 'critical defect size' is less than the wall thickness then the NDE emphasis is on the measurement of flaw height in the through thickness direction.

The critical defect size before disruptive failure is dependent on both the stressing conditions and metallurgical considerations. Thus the NDE requirements will vary within different parts of a pressurised component and could change during the life of the plant if ageing or other metallurgical factors can lead to a deterioration in inherent toughness.

The safety arguments for the pressurised components of nuclear reactors are based on fracture mechanics arguments. It is sometimes difficult to sustain a leak before break argument and this places more emphasis on the reliability of the non destructive examination. Although radiography and surface examination techniques are used during manufacture, the need to ensure that flaws cannot grow to critical dimensions during operation has led to an increased emphasis on the reliability of ultrasonic examination.

2. Definition of Inspection Reliability

The measurement of inspection reliability is difficult to assess as the influence of such factors as human performance, equipment malfunction and intrinsic technique capability are difficult to quantify. The role of these different factors will differ with the type of inspection. Thus, for instance, human factors could be expected to play a more significant role in manual inspections compared with automated inspections. For an automated inspection greater emphasis must be placed so that any equipment malfunction is fail-safe. Additionally, during either a manufacturing or an in-service inspection environmental conditions and time constraints can play an important role. Thus any reliability assessment must take into account the type of inspection in addition to the flaw sizes and degree of assurance required from the inspection.
There is a view that at the manufacturing stage the inspection standards should reflect good practice for the component being fabricated but that for in-service inspection the standards should be aimed at ensuring the continued safe or reliable operation of the plant. This is reflected in some of the code requirements. For instance ASME III(1), the construction code for nuclear vessels, stipulates that no planar defects are permitted but the in-service inspection code ASME XI(2) allows some flaw indications irrespective of the flaw type. This concept is reflected in the Central Electricity Generating Board (CEGB) submission at the Public Inquiry for the Sizewell 'B' reactor(3). The manufacturing acceptance standards are near the NDE capability limits but the fitness-for-purpose standards which relate to plant safety requirements, are related to the critical defect size determined from fracture mechanics considerations.

In its first report 'An Assessment of the Integrity of PWR Pressure Vessels' the Marshall Committee(4) argued that the probability that flaws can influence the structural integrity of any structure is the product of two functions: (a) the probability that a flaw will be present after manufacture or during service operation, and (b) the probability that ultrasonic inspection can detect the flaw. Collier and Whittle(5) have developed this concept further and have argued that the product of the chance of a flaw being present after manufacture and the chance of that defect being missed during inspection should be essentially constant. Thus they argue that the NDT procedure should have a higher probability of detecting and correctly characterising flaws which on the basis of metallurgical and fabrication knowledge are most likely to occur during manufacture compared with flaws which are highly unlikely or have a significantly lower probability of occurring during manufacture.

During any inspection process there is a need to:

(a) Detect and locate flaws,

(b) To size flaws within specified tolerances

(c) To sentence flaws according to appropriate standards.

For reliable inspection all three stages must be successfully completed. These requirements have led to various definitions of reliability. For instance the Second Marshall Committee(6) report differentiates between effectiveness and efficiency. Effectiveness is defined as the ability of any given NDE technique to successfully detect and reject flaws of concern whilst an efficient technique will not reject flaws which are not of structural concern. These factors were recognised in the PISC trials(7,8) which analysed the results from different teams with respect to three distinct criteria, i.e., correct detection of flaws, correct rejection of flaws and the correct acceptance of flaws. Taken together these criteria clearly differentiate between techniques which can categorise flaws as rejectable or acceptable according to a given criteria.

Haines(9) has defined reliability as the product of capability, repeatability and reproducibility. Capability is defined as the intrinsic ability of the NDE to detect and characterise defects, reproducibility as the ability of a number of inspectors to get the same result from a given procedure and
repeatability as the ability for the same inspectors to get the same result a number of times using the same NDE procedures.

Hemsworth(10) has pointed out that reliability in inspection can mean different things to different people. For instance the NDE operator is concerned about the reliability of the equipment. The designer or project engineer is interested in defining reliability of inspection in terms of its impact on the structural integrity of the component and will therefore include the inherent capability of the NDE procedure as well as human and equipment factors. The plant operator will include such factors as cost effectiveness in relation to outage time and loss of output in his definition of a reliable inspection.

It can be seen that there is no unique definition of inspection reliability. It depends on a variety of factors, some of which are dependent on technical matters whilst others stem from managerial considerations. Again the significance of the technical factors will depend on the material being examined, the type of component, and the standards being applied.

Before considering the role played in round robin tests on reliability of inspection it is appropriate to consider the method of manufacturing of test specimens.

3. Manufacture of Round Robin Test Specimens

Calibration test samples for NDE are generally based on geometric reflectors, ie side drilled holes, flat bottomed reflectors or EDM slots. This is usually specified in the relevant code requirements which generally stipulate that the calibration of equipment must be carried out on test blocks which simulate the metallurgical condition and section thickness of the component being examined.

Operator qualification test samples are generally on standard section thickness containing some natural or artificial flaws. Thus, for instance, most of the UK-CSWIP ultrasonic weld test samples(11) are on 15-40mm thick samples containing weld flaws, eg slag, porosity cracks, lack of fusion flaws etc. For thick wall inspection of nuclear components the CEGB(12) call for additional operator qualification tests on sample sections representative of the components being examined. This concept of testing operators on full-scale samples has been followed by organisations which validate the inspection procedures and operators for nuclear applications(12).

It is of interest to consider how welding defects are produced in thick plate fabrication, their significance from an NDE and structural integrity point of view and how they have been produced during the manufacture of thick plate samples for round robin testing.

3.1 Types of Flaws

As stated earlier ultrasonic techniques are generally calibrated on the basis of signal amplitude from either side-drilled holes or flat bottomed hole reflectors. In practice the signal amplitude from manufacturing flaws is a complex function. It will depend on the relative amplitude of the specular reflection from the sides of the flaw and crack tip signals from the flaw.
edges. The specular reflection is dependent on the flaw inclination with respect to the incident beams, the flaw dimensions, flaw surface roughness and the reflectivity of the surface. Thus round robin test specimens used to compare the capability of NDE techniques usually cover a range of flaw types. These generally fall into two categories: non-planar flaws and planar flaws.

3.1.1 Non-planar Flaws

From a structural integrity point of view flaws of this type, eg slag or porosity are not as harmful as planar flaws, eg cracks. However, crack-like flaws are sometimes associated with non-planar flaws and the latter can mask or interfere with the ultrasonic examination of other flaws. The extent to which this occurs is dependent on the specific geometry.

Both submerged arc and metal arc welding processes are prone to slag inclusions. These can be in the form of discrete particles or continuous slag lines. In practice slag inclusions can be readily reproduced by filling with powdered slag a recess in the weld bead of an area built up with manual metal arc (MMA) welding. The slag is fused during subsequent welding. However, grinding a groove in the wall of the weld preparation of the required length of inclusion and allowing slag to fill this naturally during welding gives the best control of size and position. Allen and Blanford(13) argue that these techniques are open to the objection that the groove determines the defect shape. They prefer to produce slag inclusions by modification of the welding procedure.

Several techniques are available for producing porosity(14,15). They all involve modification of the welding procedure. For instance a cavity is made in the weld and this is filled by welding using either the "metal inert gas" technique or the "tungsten-inert gas" technique with reduced gas flow, or the use of damp manual metal arc electrodes or damp submerged-arc flux. Good results are also obtained by submerged-arc welding without flux cover in the zone where porosity is required.

The volumetric or non-planar flaws discussed to date can readily be introduced into any test assembly by modification of the welding process. They can be introduced in-situ during fabrication of the test assembly or made into coupons which are subsequently implanted into the test assembly as discussed in Section 3.2.

3.1.2 Planar Defects

Planar flaws are of two general types, ie smooth or faceted. They are generally crack-like and are formed due to either poor workmanship or metallurgical factors or a combination of these factors. From an ultrasonic point of view a smooth flaw is one where the individual facets of the flaw are comparable to the wavelength of the ultrasonic. In practice this definition will include lack of side wall fusion, some form of weld cracks and fatigue cracks. From an ultrasound point of view rough cracks are multifaceted cracks or complex cracks, eg craze or intergranular solidification cracks.

3.1.2.1 Smooth Planar Flaws

Lack of side wall fusion or lack of inter-run fusion flaws arise from poor
control of the welding process or the use of incorrect welding procedure. Although lack of side wall fusion is generally smooth, interrun lack of fusion is usually of an irregular shape. Slag entrapment is sometimes associated with lack of fusion and occasionally cracking can initiate at the root.

Lack of side wall fusion can be conveniently simulated, but in an artificial manner, and positioned close to the fusion face with a high degree of accuracy by machining a recess in the weld preparation (15). The flaw shape, surface roughness and tilt can, within limits, be readily varied. Alternatively, by modifying the welding process, natural lack of fusion can be produced (14), e.g. by building up using the "metal inert gas" technique at below normal currents.

Although the method described above can be applied to any weld preparation, there are restrictions to the range of orientations, tilt, etc. which can be applied. These limitations are largely removed using implant techniques. Using diffusion bonding techniques, coupons containing planar flaws of varying sizes and surface roughness have been prepared and implanted into test pieces (16, 17, 18). With these techniques the surface roughness, size and shape of the flaws can be controlled to very close limits (typically 0.1 mm). This approach lends itself readily to the preparation of multiple planar flaws. It is claimed that reflections from the diffusion bond between the two faces of the implant are insignificant but the flaw edges can in some cases be sharply defined. This difficulty has been overcome by CETIM in France (19). In this case the flaws are machined into the two faces of the implant as previously but bonding is achieved by forge welding rather than diffusion bonding. In this way the edges of the flaws are tight and more representative of certain kinds of natural crack edge.

Smooth cracks can also be produced by either mechanical fatigue using bend or compact tension specimens or by thermal fatigue (20). By varying the starter notch configuration the aspect ratio can be varied and within limits the crack morphology can be changed by varying the loading cycle. Generally speaking the crack front is semi-elliptical but straight fronted cracks can in some instances be produced by side grooving. The crack depths and sizes can be closely controlled.

Cracks have also been produced by cathodically charging electron beam welds with hydrogen (21). The resulting cracks are normally tight and planar, with little branching. Care must be taken however to ensure that porosity does not occur at the crack tip. If this occurs the amplitude of the ultrasonic signal from the pore can exceed that from either the crack faces or the crack tip.

3.1.2.2 Faceted Planar Flaws

Unless they are favourably orientated to the incident ultrasonic beam smooth flaws are more difficult to detect than multifaceted flaws when a reflected signal can be expected from the individual facets of the flaw. Multiple smooth flaws can however behave ultrasonically like a faceted crack and the method of simulating such flaws are similar to those described in section 3.1.2.1.

Weld contamination techniques have been used to produce faceted cracks. Examples are contamination of the weld pool using copper (15), nickel (23) and
sulphur(13). These techniques generally produce clusters of intergranular cracks. Solidification cracks can be produced 'naturally' by making a deep narrow submerged arc weld bead using high current and travel speed(14). The method is however uncertain and other workers have used the same technique but using sulphur as a crack promoter.

Hydrogen cracking occurs at low temperature in both weld metal and the heat affected zone. Weld metal cracking or 'chevron' cracking has been produced in-situ by modification of the welding procedure. It is claimed that this type of flaw can be reliably produced in the laboratory(23). Heat affected zone cracking can be produced by using the opposite of what is normally considered to be good welding practice. For example, welding using damp rutile electrodes without preheat at low heat input produces cracking in susceptible material. The cracks produced are representative of service cracks but in practice are difficult to control and the process is time consuming.

3.2 Fabrication of Test Samples

There is a consensus view that any round robin test programme should include test specimens whose geometries simulate the essential features of reactor geometry, in so far as they significantly influence the ultrasonic inspection. This is particularly the case for automated inspections. The capability and reliability of the NDE technique is dependent on the system as a whole including the type of transducer array, the scanning pattern, the manipulators, the data processing as well as the skill of the operators. Thus the PISC II programme(8) included a full size PWR nozzle/shell inlet weld. Such specimens can weigh about 20-30 tons and are costly to produce.

The specimens used in the early round robin programmes were destructively examined but apart from cost considerations there are advantages if the capability of the NDE technique can be assessed without the need for detailed sectioning. The test specimens can be re-used and kept as a test vehicle for assessing and comparing the capability of any new or advanced examination techniques.

Many of the techniques discussed in section 3.1 can be used for producing flaws in-situ, ie by modification of the welding process. However subsequent destructive examination has shown that there can be significant differences between the intended flaw size and that measured during destructive examination. In some cases it was found that some of the flaws produced by the techniques described earlier were not in the intended location and in some cases the flawed volume was as much as twice that intended. These difficulties can be largely overcome by manufacturing small coupons containing the flaw, eg cracks, slag etc. The flawed components can be non-destructively examined using high sensitivity techniques prior to implanting in the main weld.

Several techniques have been used to assemble these flawed coupons into the main weld. In some of the earlier tests the flaws were assembled into a strip which was then welded into the main test assembly(24,25). Later test assemblies have made extensive use of the simulated flaws, discussed in
section 3.1.2.1, which are implanted directly into the weld (Fig 1). In other cases a combination of both techniques have been proposed. In this case the flaw assembly is welded into a cuboid which is then assembled into a flaw strip prior to welding into the completed test assembly(15) (Fig 2).

With all implant techniques there is a risk that the implant weld can either cause crack propagation or could alter the crack tip configuration. Additionally satellite defects in the implant welds can 'picture frame' the intended flaw or could mask the flaw thus making subsequent examination difficult.

4. Round Robin Test Programmes

Several national and international test programmes have been carried out to determine both the capability and reliability of NDE to detect and size flaws in steel sections. Some of these have involved large numbers of operators on a variety of test samples. Several of these series of tests(26,27) have been carried out on section thicknesses and material conditions which are not representative of the thick sections of interest in this paper. Some tests have been carried out on thick sections which are of direct relevance to the requirements of the nuclear industry and it is proposed to review the results obtained from these test programmes.

4.1 US Pressure Vessel Research Committee Programme

In the mid-1960s the US Pressure Vessel Research Committee (PVRC) initiated an extensive programme aimed at establishing automated ultrasonic techniques which can detect, locate and size flaws in thick walled ferritic steel components. The techniques were essentially aimed at the in-service inspection.

Several test specimens, varying in thickness from 120-270mm, were butt welded in such a way that a spectrum of welding flaws (porosity, slag, lack of fusion and cracking) were introduced during the welding process.

During the period 1967-68 four butt welds and four nozzle welds containing defects were ultrasonically examined, by five teams from different organisations. These teams had the option of using their own examination procedures or using the procedure in the then current codes (ASME Section III, Appendix IX). It soon became apparent that control of test parameters was required to permit a comparison of the data. Therefore, the reporting level was set at 25% DAC, the specific angle beam transfer method was recognised, and one couplant, glycerine, was selected. Even with the control of these variables, it was found that there was virtually no agreement amongst the teams reports. As a result of this lack of agreement, steps were taken to further control several additional parameters which became known as the 'new procedure'(28).

Subsequent tests were carried out with these standardised procedures. The results have been reported on the basis of the test sample and this method is repeated in this report.
4.1.1 PVRC Specimen 201

Specimen 201 consisted of a nominal 200mm plate joined by a manual metal arc butt weld. Ten flaws were introduced into the plate but two plate laminations adjacent to the weld were included in later studies. Subsequently half the test plate was weld clad and re-examined using the standardised ultrasonic (UT) procedure. The results(28) showed that the cladding seriously perturbs the ultrasonic examination and specific correction factors are necessary to correct these effects. The ultrasonic data yielded nominal flaw location but did not give flaw dimensions.

4.1.2 PVRC Specimen 251J

This test plate consisted of two 280mm thick plates welded together using a submerged arc process. Fifteen weld defects (slag, transverse cracks and longitudinal cracks) were deliberately introduced into the weld. The tests were done to examine problem areas highlighted in the tests in specimen 201. The effectiveness of 45°, 60° and straight beam probes were examined from both the clad and unclad facing using the old and new standardised procedure.

The results have been analysed by Buchanan(29) using a defect identification criteria consisting of adding tolerances to the intended defect dimensions. If the ultrasonic dimensions reported fell within the prescribed tolerances then it was assumed as a correct defect identification. A big variation was again reported between team performances although some teams were significantly and consistently better than others. The new standardised PVRC procedure was better than the old procedure and there was little or no difference in detection capability from either the clad or unclad condition.

4.1.3 PVRC Specimens 155, 202 and 203

During 1974 a new programme was initiated using a UT procedure based on Appendix I of the ASME Code Section XI. The specimens used were: a nozzle shell weld containing five flaws (specimen 155), a butt weld purported to contain lack of fusion, slag and cracking flaws (specimen 202) and a second nozzle to shell weld again containing slag, lack of fusion and some cracks (specimen 203).

Thirteen inspection teams reported data. Initial results were not encouraging. A review of the available radiographic data indicated that the size, shape and location of the actual flaws differed significantly from that intended during fabrication. In view of these factors a two-point coincidence method was developed to determine if a given ultrasonic indication was correct or not without assuming actual flaw location(30). It consisted of an analytical division of the specimen into a large number of small essentially cubic elements. If any portion of two or more indications fall within a given element a discontinuity is said to exist and all indications within that element are treated as correct indications. The coincidence method showed that 60 to 80% of the data points were confirmed by another data point.

4.2 PISC I Programme

The growing interest in Europe on the effectiveness of ultrasonic testing of thick plate led to discussions between EEC/OECD and PVRC for European
participation in the PVRC programme. As a result of these discussions the PVRC offered three plates to the OECD Committee of the Safety of Nuclear Installations (CSNI) and this led to the formation of the Plate Inspection Sub Committee (PISC) of CSNI. During the second half of 1974 an invitation was issued for participation in a round robin test programme. Thirty-four inspection organisations from ten countries agreed to participate in the test programme.

PVRC supplied two flat plates and a nozzle specimen. Each test specimen or plate contained a weldment containing deliberately implanted flaws. The flaw distribution was not known to the inspecting teams at the time of the inspection. After completion of the inspection each plate was destructively examined and the results reported by the inspection teams compared with that obtained after sectioning.

Each inspection team was asked to inspect and to report the results on an agreed format using an inspection procedure based on the 1974 ASME XI NDE procedure. This required participants to report signals above 20% DAC. Due to the metallurgical conditions of the plates this resulted in a large amount of data and increased the inspection time. After this procedure had been followed by a total of thirteen teams it was decided to adopt a reporting level of 50% DAC for the remainder of the programme. The NDE technique used by some of the participants differed from the minimum requirements of ASME XI procedure and after completion of the initial phase participants were allowed to re-inspect the plates with 'alternative' NDE procedures.

The inspections started in April 1976 and were completed in June 1978 when the plates were sent to the Joint Research Centre of the Commission of European Communities at ISPRA for destructive examination. The results were reported(7) in September 1979.

4.2.1 The Test Plates

Three test plates were provided by the PVRC for the European test programme: two nominally flat plates (coded 50/52 and 51/53) and a third plate incorporating a forged nozzle, (coded 204). All the weldments in the plates contained flaws deliberately implanted during the welding process. Details of the plates are given below:

(a) Plate 50/52

Fabricated from two pieces of SA-302 Grade B, Mn-Mo steel, the two pieces being butt welded together by the electroslag method with the weld containing gross cracks. The welded plate measured 140.3cm x 92.7cm x 24.4cm and weighed 2586 kg.

(b) Plate 51/53

Fabricated from two pieces of SA-302 Grade B, Mn-Mo steel, the two pieces being butt welded together by the submerged arc method with the weld containing gross cracks.

The welded plate measured 104cm x 91cm x 20cm and weighed 1517 kg.
This plate was supposed to be quenched, tempered and stress relieved after welding but doubts remain about this as a great deal of trouble was encountered during final cutting when the plate bent owing to residual stresses, trapping the saw blade.

(c) **Nozzle plate 204**

The nozzle plate measured 102.6cm x 102.6cm x 21cm and contained a 457cm forged nozzle which protruded 22.9cm above the top plate surface, the nozzle bore being unmachined at 15.2cm diameter. The total weight was 1944 kg. The nozzle was welded in place by manual metal arc methods with the weld containing nine discreetly implanted flaws.

### 4.2.2 Method of Analysis

The programme generated a vast amount of data and the agreed reporting format allowed a computer programme to be written which allowed a comparison of the NDT results with those obtained from the destructive examination. Emphasis was placed on the precision of detection, location and sizing of each defect and allowed an evaluation of the correct rejection or acceptance of the defects according to the ASME XI (IWB-3500) 1974 standards. The main parameters used to present the analysis are given below:

**DDP.** The defect detection probability is the probability that a team, chosen at random, detects a particular defect. This is estimated as DDP = n/N where n is the number of successful detections and N is the number of teams who participated. Confidence limits are constructed using the binomial distribution in the usual manner.

**CRP.** The correction rejection probability is the probability that a team, chosen at random, correctly rejects a particular rejectable defect. This is estimated by the ratio CRP = r/N where r is the total number of teams correctly rejecting the defect according to a symbolic use of the rejection criterion of ASME Code Section XI IWB 3500. N is the total number of teams participating. As for DDP confidence limits are constructed using the binomial distribution.

**CAP.** The correct acceptance probability, is the probability that a team correctly accepts an acceptable defect. This is estimated as CAP = P/N where P is the total number of teams correctly accepting an acceptable defect and N is the number of teams who participated. No credit is given if a team fails to detect a defect.

### 4.2.3 Results using PISC modified ASME XI Procedure

The results of the destructive examination show that the defects in the three plates fall naturally into three main groups:

(i) Small volumetric defects with a maximum size of 10mm. These defects would be acceptable according to the ASME criteria.

(ii) Planar defects 11-273mm in through thickness dimension which would have been unacceptable or referable according to the ASME criteria.
(iii) Composite sets of defects made up from a number of flaws which when classified according to ASME XI proximity rules would result in them being classed as unacceptable defects.

The defect detection probability for each flaw is shown in Fig 3a. It can be seen that there is a large scatter in detection probability of the acceptable flaws less than 10mm in through thickness direction. The probability of detection of planar rejectable flaws less than 20mm in through thickness direction is less than 50% and only approaches 90% for flaws in excess of 60mm in through thickness direction. There are insufficient defects in the 20–50mm through thickness range to make any prediction of detection probability. The results obtained for the composite defects are not good. Composite defects with a through thickness dimension of 120mm have a detection probability of less than 50%.

The results based on correct rejection probability are less encouraging (Fig 3b). None of the composite defects were classified as rejectable although the effective through thickness dimension, according to the ASME proximity rules, could be as high as 150mm. No planar ASME referable flaws less than 15mm in through thickness dimension were correctly classified and flaws 55mm in through thickness direction had a correct rejection probability of between 95% and 60%.

The defect detection probability varied with position in the plate thickness (Fig 4). It can be seen that best results were obtained when the defects were near the back wall. The defect detection in the near surface, i.e. in the sub-clad region, was poor.

There was a significant tendency to oversize small or acceptable defects and to undervalue the larger rejectable defects.

4.2.4 Results using the Alternative Procedure

The second phase of the PISC I programme allowed teams to re-inspect the plates using alternative procedures to the PISC or modified ASME procedure. Some of these were techniques used by European teams for the in-service inspections of their national programmes, and included additional probe angles, i.e. 70° longitudinal probes, or tandem probes. Some techniques were in an advanced state of development, e.g. holography. The results of DDP are given in Fig 5a and for CRP in Fig 5b.

Comparing Figs 3 and 5 it can be seen that there is a significant improvement in both the defect detection probability and in the correction rejection probability. Some individual techniques correctly classified all the rejectable defects (Fig 6), e.g. teams JN29 and MF54. Both teams used high sensitivity techniques, 70° longitudinal probes and tandem techniques. Good results were also obtained by the teams using focused probes.

4.3 The Defect Detection Trials

The PISC I programme had shown that using the minimum requirements of the ASME XI procedure some of the inspections failed to detect or categorise all the defects requiring further investigation according to the code requirements. Although an improved performance was reported using alternative procedures, it
was felt there was a need for a further collaborative round robin programme, (PISC II). As the PISC II programme was not expected to be completed until 1983/84 there was a need in the UK for a further round robin exercise to demonstrate that the NDE techniques which could be used in the Sizewell 'B' reactor were capable of correctly detecting and correctly classifying significant flaws. The NDE techniques examined in the test programme were selected on the basis of the results obtained in the alternative PISC trials and techniques in an advanced state of development which could be applied to the proposed Sizewell 'B' reactor.

The inspectors had no prior knowledge of the number, size or location of any of the flaws in the test specimens. Each inspection team was asked to submit its NDE procedure prior to start of the inspections and the inspections were witnessed by independent invigilators.

The tests were done in two phases. Phase I consisted of two flat plate specimens 1.5m x 1.5m x 250mm containing a submerged arc butt weld and flaws with a through thickness dimension in the range 10-50mm, were deliberately introduced into the weld area. Phase II of the programme was aimed specifically at the effectiveness of the NDE techniques to detect and size flaws in the near surface region. After welding and insertion of flaws each test plate was strip clad to the then current RPV procedure. The method of manufacture of the test specimens was arranged so as to allow an assessment of the effectiveness of the NDT techniques prior to destructive examination of the test samples.

4.3.1 Phase I Inspection

As is stated earlier the inspection techniques used in the DDT were based on the techniques used by the best performance teams in the PISC I alternative procedure trials. Seven inspection teams participated. They fell into three areas:

(a) High sensitivity pulse echo techniques (typically 10% DAC) supplemented by 70° longitudinal probes for the near surface examination and advanced sizing techniques.

(b) High sensitivity pulse echo combined with tandem techniques with advanced sizing techniques.

(c) Time of flight diffraction techniques (TOFT). Although in the laboratory development stage this technique was included in the trials as it is not dependent on specular reflection from the crack face.

The results(31) from the best teams were very encouraging. All the three basic inspection techniques examined are capable of detecting and accurately sizing flaws with a through thickness dimension within a few millimetres of the intended size. Taken as a whole all seven teams detected all the defects from the clad face examination. In most cases the volume identified for further examination was large. The accuracy of subsequent refinement of location and sizing differed markedly between teams. The best results were obtained by teams who used complementary analytical procedures including precision ranging of crack tip signals.
4.3.2 Phase 2 Inspections

For this phase two test specimens were prepared containing defects with a through thickness dimension in the range 3-30mm from the clad base metal interface. The first test specimen had a flat plate geometry which was intended to represent the core barrel of the RPV, whilst the second test specimen was machined to simulate the profile of the inner radius of the reactor inlet nozzle.

Three teams examined the flat plate specimen. One team used manual assisted techniques as would have been applied during fabrication but the other two teams used automated scanning and data processing techniques. The best results on the first test piece were obtained by the automated inspections. The optimum NDT technique used a search system based on the 70° longitudinal wave examination with precision ranging of crack tip signals and time of flight diffraction to determine the defect location and size. Using this technique the defects were located accurately and the defect depth measurements were within 1-2mm of those reported from the destructive examination.

Only the automated techniques were used on the specimen representing nozzle inner radius. The results obtained on this test piece were encouraging. Both teams detected all the defects, although due to human error one team did not report one of the defects. The accuracy of the through thickness depth measurement was generally within a few millimetres. Due to faulty design of the manipulator one team underestimated the depth of one defect.

The results(31) from this phase of the work show that with optimised techniques all defects with a through thickness dimension in the range 5-30mm can be detected, located and sized within a few millimetres. Sub-surface defects in the size range 3-5mm can be detected but can only be sized as less than 5mm.

4.4 PISC II Programme

The increased emphasis of the role of NDE in the safety of nuclear reactors led to joint sponsorship of the PISC II programme by CSNI and CEC. It was recognised that there were gaps in the flaw range of interest in the PISC I programme and there was a need to extend the work from the flat plate geometry to more complex geometries, i.e nozzle to shell welds. The study included NDE techniques which had been used or could be used for acceptance tests, pre-service or in-service inspection. The test specimens included flaws in the near surface region with a through thickness dimension between 3mm and 40mm and internal buried defects with a through thickness dimension between 2% and 35% of the plate thickness.

Four test specimens were included in the programme. Two were flat plate specimens (plates 1 and 2) and two were nozzle/shell welds (plates 3 and 9). Both the flat plate and nozzle to shell plates contained flaws which simulated both manufacturing and in-service defects. After completion of the inspections, test plates 1, 2 and 9 were destructively examined but it was judged that the method of flaw manufacture on plate 3 and the results from the advanced radiographic examination were adequate for the analysis of the NDE data. At the start of the programme it was expected that the base material
would be free from flaws which could interfere with the NDE examination. This was the case for plates 2, 3 and 9 but one part of plate 1 contained manganese sulphide inclusions which complicated both the inspection and the subsequent analysis.

The round robin tests were held during 1982 through to part of 1984. Inspection teams from the USA, Japan and Europe participated in the trials. These teams used a variety of techniques and these were analysed with respect to their ability to detect, locate and size the defects present in the test plates. The ASME Section XI procedure was again included among the techniques used in order to establish a point of reference with PISC I, and to examine the effect of modifications such as higher sensitivity, the use of supplementary probes, e.g. 70° longitudinal probes etc on this procedure.

The results were analysed in a similar manner to PISC II, i.e. on the basis of Defect Detection, Correct Rejection and Correct Acceptance of flaws. Several new parameters have been introduced to analyse the results of specific techniques or teams. Thus DDF refers to the detection rate for that technique on all the flaws, i.e. DDF = d/D where d is the number of flaws detected and D is the number of flaws present. Sometimes it has been necessary to restrict analysis to the number of rejectable flaws detected DDFR. The decision on whether a defect was accepted or rejected was on the basis of ASME XI IWB 3510 criteria 1974, i.e. the same basis as PISC I.

4.4.1  NDE techniques based on ASME Procedures

The PISC II results (8) have been analysed on the basis of techniques in the 'spirit of ASME' and 'special procedures'. The former comprise pulse echo techniques based on 45, 60 and 0° pulse echo scanned in two directions parallel and perpendicular to the weld. In this analysis the influence of scan sensitivity and the use of supplementary techniques, e.g. 70° longitudinal probes and tandem, have also been examined.

There is clear evidence that both the defect detection probability and the correct rejection probability is a function of reporting level (Fig 7a and 7b). For each of the four plates there is a significant improvement in the results as the reporting level is increased from 50 to 20% DAC. There is no further improvement if the reporting threshold is further increased to 10% DAC. At 10% DAC there was a tendency to increase the false call rate and to reject several acceptable defects. It would be premature, however, to conclude that 20% DAC is the optimum sensitivity. Indeed, several special procedures (see 4.4.2) used sensitivities higher than 10% DAC and obtained excellent results.

There is a significant improvement in the results if a 70° longitudinal and tandem probe were included in the inspection techniques. Improvements occurred at all recording levels but were most significant at the 50% and 35% DAC level. These results are illustrated from the results of one team who used a variety of techniques (Table 1).
<table>
<thead>
<tr>
<th>Team</th>
<th>Procedure Code</th>
<th>DDF</th>
<th>CRF</th>
<th>CAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECO05499</td>
<td>10% DAC M,B,S,TD</td>
<td>1.0</td>
<td>1.0</td>
<td>.67</td>
</tr>
<tr>
<td>ECO00699</td>
<td>20% DAC M,U</td>
<td>.94</td>
<td>1.0</td>
<td>.87</td>
</tr>
<tr>
<td>ECO02599</td>
<td>20% DAC M,C,TD</td>
<td>.94</td>
<td>.83</td>
<td>.67</td>
</tr>
<tr>
<td>ECO01699</td>
<td>20% DAC M,U,S,TD</td>
<td>1.0</td>
<td>1.0</td>
<td>.67</td>
</tr>
<tr>
<td>ECO05399</td>
<td>20% DAC M,B,S,TD</td>
<td>1.0</td>
<td>1.0</td>
<td>.40</td>
</tr>
<tr>
<td>ECO05099</td>
<td>35% DAC M,B,S,TD</td>
<td>1.0</td>
<td>.83</td>
<td>.93</td>
</tr>
<tr>
<td>ECO01199</td>
<td>50% DAC M,U</td>
<td>.56</td>
<td>.5</td>
<td>.93</td>
</tr>
<tr>
<td>ECO03099</td>
<td>50% DAC M,C</td>
<td>.56</td>
<td>.42</td>
<td>1.0</td>
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<tr>
<td>ECO01299</td>
<td>50% DAC M,U,S</td>
<td>.61</td>
<td>.75</td>
<td>1.0</td>
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<tr>
<td>ECO05699</td>
<td>50% DAC M,U,S,TD</td>
<td>.78</td>
<td>.92</td>
<td>.87</td>
</tr>
<tr>
<td>ECO05799</td>
<td>50% DAC M,C,S,TD</td>
<td>.83</td>
<td>.92</td>
<td>.93</td>
</tr>
<tr>
<td>ECO04899</td>
<td>50% DAC M,B,S,TD</td>
<td>.83</td>
<td>.92</td>
<td>.8</td>
</tr>
</tbody>
</table>

Legend: M - manual inspection  
U - examination from unclad side  
C - examination from the clad side  
B - examination from both clad and unclad side  
S - supplementary 70° probes  
TD - tandem probes

The results discussed to date refer in the main to the flat plate specimens. It should be noted that the results obtained on the nozzle/shell weld Plate No 3 (Table 2) are not as good as those obtained on the plate/plate specimens. This is attributed to the complex geometry of the test specimen and to the nature of the defects.

4.4.2 NDE Results based on Special Procedures

The special procedures used in the PISC II trials consisted of a variety of techniques. Some techniques used high sensitivity pulse echo techniques for defect detection and a range of advanced techniques for sizing. Other systems used 'advanced' techniques for both detection and sizing, eg use of focused probes or time of flight diffraction techniques. In general most of the techniques considered in this section of the paper used automated inspection techniques.
TABLE 2

<table>
<thead>
<tr>
<th></th>
<th>MDDF</th>
<th>MCRF</th>
<th>MCAF</th>
</tr>
</thead>
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<tr>
<td>ASME 10% DAC (all)</td>
<td>.77</td>
<td>.60</td>
<td>.62</td>
</tr>
<tr>
<td>ASME 20% DAC (all)</td>
<td>.75</td>
<td>.49</td>
<td>.78</td>
</tr>
<tr>
<td>ASME 50% DAC (all)</td>
<td>.35</td>
<td>.07</td>
<td>.97</td>
</tr>
<tr>
<td>ASME 20%, M, U</td>
<td>.53</td>
<td>.36</td>
<td>.88</td>
</tr>
<tr>
<td>ASME 20%, M,C,S</td>
<td>.68</td>
<td>.43</td>
<td>.77</td>
</tr>
<tr>
<td>ASME 20%, M,B,S</td>
<td>.75</td>
<td>.41</td>
<td>.79</td>
</tr>
</tbody>
</table>

Mean values for DDF, CRF and CAF for all teams

Taking the mean of the special techniques, there is a tendency for these to perform better and to reduce the sizing error when compared with the previous results, ie 20% DAC using ASME techniques. Some special techniques performed very well and DDF, CRF and CAF of unity were reported on plates 1 and 2.

This trend for individual special teams to give better results than those reported for the techniques using 20% in the 'spirit of ASME' is more pronounced when one considers the results obtained from the nozzle/shell weld plate No 3. (Table 3)

TABLE 3

<table>
<thead>
<tr>
<th>Team</th>
<th>Procedure</th>
<th>DDF</th>
<th>DDFR</th>
<th>CAF</th>
<th>CRF</th>
</tr>
</thead>
<tbody>
<tr>
<td>BDO05599</td>
<td>Complex combin. of techniques</td>
<td>.97</td>
<td>1.0</td>
<td>.96</td>
<td>.86</td>
</tr>
<tr>
<td>EF003699</td>
<td>ASME 10% DAC+suppl. techniques</td>
<td>.94</td>
<td>1.0</td>
<td>.62</td>
<td>1.0</td>
</tr>
<tr>
<td>LNO09199</td>
<td>TOFD</td>
<td>1.0</td>
<td>1.0</td>
<td>.38</td>
<td>.93</td>
</tr>
<tr>
<td>SROOA299</td>
<td>Complex combin. of techniques</td>
<td>.97</td>
<td>1.0</td>
<td>1.0</td>
<td>.86</td>
</tr>
<tr>
<td>VHD16199</td>
<td>Complex comb. of tech.</td>
<td>.81</td>
<td>1.0</td>
<td>.31</td>
<td>1.0</td>
</tr>
<tr>
<td>YCO08099</td>
<td>Immersion Focusing Probes</td>
<td>.80</td>
<td>.93</td>
<td>.76</td>
<td>.79</td>
</tr>
</tbody>
</table>

Some of the teams who used specialised techniques reported tolerance bands in the range ±3m or ±5mm. When these tolerance bands are included in the results there is a further improvement in performance. (Table 4)
TABLE 4

<table>
<thead>
<tr>
<th>Team</th>
<th>DDF</th>
<th>DDFR</th>
<th>CRF without tol.</th>
<th>CRF with tol.</th>
<th>CAF without tol.</th>
<th>CAF with tol.</th>
</tr>
</thead>
<tbody>
<tr>
<td>BD005599</td>
<td>.97</td>
<td>1.0</td>
<td>.86</td>
<td>1.0</td>
<td>.96</td>
<td>.96</td>
</tr>
<tr>
<td>LN009199</td>
<td>1.0</td>
<td>1.0</td>
<td>.93</td>
<td>1.0</td>
<td>.38</td>
<td>.38</td>
</tr>
<tr>
<td>SR00AZ99</td>
<td>.97</td>
<td>1.0</td>
<td>.86</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

4.4.3 Effect of defect location and type

There is a tendency to oversize small defects and to undersize large defects. When the defects from all four test places are analysed on the basis of defect type they fall into three distinct types (Fig 8a and Fig 8b). Type A defects are smooth crack like flaws with sharp crack edges, type B are rough defects or defects with blunt crack edges, whilst type C are volumetric defects. It is again significant that some of the special procedures with a good overall performance on plate 3 had the best results when the flaws are categorised according to defect type Fig 9.

Discussion and Conclusion

Although the PVRC and PISC I trials demonstrated the need for defined procedures, the 'PISC procedure' was not capable of detecting flaws which would have been classified as referable according to IW 3510 of ASME XI 1974. The alternative techniques used in the PISC trials showed that NDE techniques were available which performed significantly better than the techniques specified as the minimum requirement of the 1974 ASME XI code, on which the 'PISC procedure' was based. This conclusion was confirmed in the defect detection trials for flat plate and for the nozzle inner radius region. The main differences between the good results obtained in the Defect Detection Trials and the relatively poor results in PISC I using the 'PISC procedure' were the use of 70° longitudinal probes and high sensitivity techniques for defect detection and the use of complementary sizing techniques. These same factors were highlighted in the PISC II trials for both flat plate and nozzle/shell geometries. Indeed a feature of the tests on PISC II plate 3, the large PWR nozzle/shell weld, was the need for complementary techniques to obtain good detection and sizing results.

It should be noted that the sensitivity used at the detection stage of PISC I had to be changed from 20 to 50% because of the large number of signals produced in the base plate. A feature of successful automated techniques used in the trials discussed in this paper is the need to have data handling facilities which can differentiate between defect signals and signals from small discontinuities or geometric signals which have no structural concern. It is clear that in assessing the capability of any technique a balance is called for between the cleanliness of the base plate and the data handling capability of the equipment. The cleanliness of steel forgings which are produced by modern steel making practice is such that DAC levels of 10% can be
used but this may not be the case for some of the earlier steel productions. In these instances it may not be feasible to use the high sensitivities required to achieve the optimum NDE results.

An important conclusion of the PISC II trials is that both the detectability and the ease of sizing is dependent on flaw types. It is clear that the type, size and orientation of flaws used in any round robin exercises can have a considerable influence on the conclusions drawn regarding the capability of the NDE technique to accurately detect, locate and size flaws.

It has been argued that some of the flaws in earlier test block exercises and in plate 2 of PISC II were easy to detect and size either because the crack tip radii were blunted by the subsequent fabrication process or that the defect outlines were 'picture framed' by the presence of satellite flaws. Certainly the presence of these satellite defects compounded the sizing problems. Whilst the presence of satellite flaws can make sizing more difficult, within reason it represents the practical situation. In practice many flaws produced by a perturbation in the welds will result in a complex flaw where small flaws will be associated with a major defect. In these circumstances, satellite flaws associated with the main defect are a good representation of practice.

The most difficult flaws to detect and size were smooth flaws with sharp crack tip radii. The evidence, that the smooth sharp tip radius flaw (Type A defects in PISC II) are the most difficult flaw to detect and size, is based on simulated circular patch flaws. In practice one of the most likely types of type A defects are fatigue cracks. Typically a fatigue crack will be initiated at some discontinuity or stress raiser and the resulting cracks have a thumb-nail crack profile. The crack initiator will be closer to a PISC II type B or C defect and only the crack extension profile will be represented by a type A flaw.

These few examples highlight the need for realism in the flaws which need to be used in any test block exercise. This is clearly recognised in the PISC III programme(32) where the emphasis is on real defects. This programme should include tests on samples containing 'natural' defects from components withdrawn from service.

One of the declared aims of the PISC III programme is to assess the reliability of NDE. As is stated earlier there are different definitions of reliability. The importance of the different factors which can affect reliability depends on the objectives and types of inspection being considered. Most of the thick plate round robin exercises have not attempted to draw any statistical meaning from the results. For such an experiment to be statistically meaningful there would need to be a large number of trials for any specific defect (e.g. with regard to flaw type, size, location, orientation etc) and for any given NDE procedure. For example, to demonstrate that there was a 95% probability of success at a 90% confidence level would require 45 trials, all successful. This figure rises to 77 and 145 trials respectively if 1 and 2 failures are observed. Of the round robin exercises discussed in this report only the PISC I trials using the 'PISC procedure' had an adequate number of trials but in this case the number and types of flaws were limited. Because of this difficulty of getting quantitatively statistical data it is claimed that an improvement in reliability in NDE can
best be obtained by improving the constituent parts of the system. This philosophy has been followed in the PISC III programme and currently there are no plans to obtain quantitative statistical results for any given NDT technique or flaw type.

The PISC III programmes consist of a number of tasks. Several of these tasks are relevant to thick plate testing. For instance, it is planned that an inspection programme will be mounted at the MPA Stuttgart where facilities will be available to test remotely the ISI equipment on full-scale PWR geometries. The facility will allow the use of the mast, manipulator, probe assemblies and the data acquisition equipment which is being or can be used for in-service inspections. This will allow a clear demonstration of the capability of the NDT systems and will make a significant contribution towards the demonstration of the reliability of that system.

It has been shown that NDT techniques are capable of accurately detecting, locating and sizing flaws. To be of increased benefit to the structural integrity and fracture mechanics there is a need for better understanding of the factors which affect defect characterisation. These factors are being addressed in the parametric studies and by the theoretical modelling group in PISC III.

Before analysing the PISC II trials the Reference Laboratory corrected some obvious errors, eg errors in data transposition. The Human Reliability task group of PISC III is analysing the PISC II data and some of the planned work in PISC III to see what lessons can be learned. The aim of this work is to produce guidelines which can be applied to reduce the effect of human error in both manual and automated inspections. The work of this task force and the task force on equipment variables will make a significant contribution to our knowledge of the factors which can improve NDE reliability.

Although most of the round robin tests done to date were not aimed to get statistical reliability data, attempts have been made to use the test results to determine detection probabilities. For instance, based on the analysis made on the DDT and PISC II data Hemsworth(10) has shown that the best results from both these trials can achieve acceptable detection probabilities. Analysis of this type is valuable to obtain confidence in the NDE procedure but does not give the probability of detection or correct sizing of a given technique when used by different operators on a number of different occasions. In order to obtain statistical data of this type a large number of trials are required on the same kind of defect. It will be necessary for a number of teams to carry out repeat inspections on a number of similar defects in the test assemblies. Apart from the difficulty of making test blocks with similar defects there is a danger that the defect population will become known to the inspectors when a number of teams carry out repeat inspections on the same test assemblies.

These problems can be overcome by the use of simulators. Ultrasonic simulators are currently under development(33) which allow a simulated transducer to be scanned either manually or automatically under the control of an operator over a simulated test block. Means of monitoring the positional co-ordinates are provided and by means of pre-stored data obtained from real ultrasonic examinations on test samples the operator is presented with an ultrasonic signal consistent with the probe scanning movement carried out on
the simulator. Currently these simulators are limited to flat plate geometries but this is being adapted to complex geometries, eg nozzle to shell welds. Data from test assemblies used in round robin trials can be synthesised in any number of combinations thus limiting any 'learning curve effect'. Today it may only be possible to check the reliability of teams to analyse and interpret data but in a few years developments are in hand which will allow these techniques to give quantitative statistical data on NDE reliability. Development work of this type is to be encouraged as it will be invaluable both as a method of training and approval of NDE operators and will allow quantitative statistical information of inspection reliability.
REFERENCES:

1. American Society of Mechanical Engineers, Boiler and Pressure Vessel Code Section III.

2. American Society of Mechanical Engineers, Boiler and Pressure Vessel Code Section XI.


8. Report on the PISC II Exercise. Reports No 1 to 5 Published by the OECD Nuclear Energy Agency and the Committee on the Safety of Nuclear Installations. Reports published at a conference in Varese, October 1986.


27. Size Measurements and Characterisation of Weld Defects by Ultrasonic Testing, Parts 1, 2 and 3. Published by the Welding Institute, Abington. 1979 and 1982.


33. UK Patent No 13851 by P Stoor and P G Bentley. 'Apparatus for simulating non destructive testing equipment'.
FIG. 1 METHOD OF WELDING IN FLAW INSERTS
FIG. 2 METHOD OF FLAW IMPLANTATION IN TEST ASSEMBLIES
FIG. 3A  DEFECT DETECTION PROBABILITY AS A FUNCTION OF THE DEFECT SIZE ; PISC PROCEDURE. ( THE SOLID AND BROKEN LINES ARE DRAWN TO GUIDE THE EYE THROUGH THE BEST ESTIMATE AND UPPER AND LOWER 95% CONFIDENCE BOUNDS : THESE BOUNDS ARE DERIVED FROM THE BINOMIAL DISTRIBUTION ).
FIG. 3B CORRECT REJECTION PROBABILITY AS A FUNCTION OF THE DEFECT SIZE; PISC PROCEDURE
All defects:
- which have \( \Delta z = 2a > 4\text{mm} \)
- which are not porosities
- which are not confused

FIG. 4 AVERAGE DEFECT DETECTION PROBABILITY AS A FUNCTION OF THE DEFECT POSITION IN DEPTH
FIG. 5a DEFECT DETECTION PROBABILITY AS A FUNCTION OF THE DEFECT SIZE; ALTERNATIVE PROCEDURES
FIG. 5b CORRECT REJECTION PROBABILITY AS A FUNCTION OF THE DEFECT SIZE; ALTERNATIVE PROCEDURES
<table>
<thead>
<tr>
<th>TEAM</th>
<th>DD</th>
<th>CA</th>
<th>CR</th>
<th>PLATES EXAMINED</th>
<th>PROCEDURE</th>
</tr>
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<tr>
<td>REF</td>
<td>a</td>
<td>b+</td>
<td>c</td>
<td>d</td>
<td>50 50 50 52 53</td>
</tr>
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<td></td>
<td></td>
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<td></td>
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<td>14</td>
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<td>PISC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15</td>
</tr>
</tbody>
</table>

1. AUTOMATIC SCANNING OF THE PLATES
2. MANUAL SCANNING OF THE PLATES
3. USE OF FOCUSED PROBES AS AN IMPORTANT CHARACTERISTIC OF THE PROCEDURE
4. NATIONAL STANDARD OR PROCEDURE IN THE SPIRIT OF ASME CODE (FOR PSI OR MANUFACTURING INSPECTION)
5. HIGHER SENSITIVE ECHO TECHNIQUE(S) THAN ASME CODE AS A MAIN CHARACTERISTIC OF THE PROCEDURE
6. TANDEM TECHNIQUE(S) AS A MAIN CHARACTERISTIC OF THE PROCEDURE
7. USE OF SPECIAL PROBES (TWIN CRYSTAL, 70° LONGITUDINAL, 35° SHEAR WAVES . . . )
8. USE OF SOPHISTICATED TECHNIQUES (HOLOGRAPHY, HIGH FREQUENCY, BACK SCATTERING, DELTA, TRANSIT TIME, LOCUS . . . )
9. INSPECTION FROM BOTH SIDES OF THE PLATE
   a. 0 < H < 10 mm (all defects)
   b. 10 mm < 15%T (vertical cracks)
   c. 15%T < T (vertical cracks)
   d. 10 mm < T (sets of rejectable defects)

+ POPULATION DIMENSION IS 3

FIG. 6 CONSTITUENT ELEMENTS OF THE ALTERNATIVE PROCEDURES USED IN THE PISC I TESTS
Detection rate and correct rejection rate as a function of the recording level for ASME procedures
(All four PISC II plates)

MODDF  Mean value for DDF
MCRF   Mean value for CRF
FIG. 8a DETECTION AS A FUNCTION OF DEFECT SIZE AND DEFECT CATEGORY.
FIG 8b REJECTABLE DEFECT CORRECT REJECTION AS A FUNCTION OF DEFECT SIZE AND DEFECT CATEGORY.
FIG. 9 AVERAGE SIZING ERROR IN THE THROUGH-THICKNESS DIRECTION AS A FUNCTION OF DEFECT CATEGORY