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Final Report of the ENIQ 2nd Pilot Study

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FINAL REPORT OF THE ENIQ 2nd PILOT STUDY

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Approved by the Steering Committee of ENIQ for publication

Foreword

The present work summarises the outcome of the activity of the ENIQ Task Group for Qualification (TGQ) on the ENIQ Second Pilot Study.

ENIQ, the European Network for Inspection and Qualification, is driven by the nuclear utilities in the European Union and Switzerland and managed by the European Commission's Joint Research Centre (JRC). It is active in the field of in-service inspection (ISI) of nuclear power plants by non-destructive testing (NDT), and works mainly in the areas of qualification of NDT systems and risk-informed in-service inspection (RI-ISI). This technical work is performed in two task groups: TG Qualification and TG Risk.

A key achievement of ENIQ has been the issue of a European Qualification Methodology Document, which has been widely adopted across Europe. This document defines an approach to the qualification of inspection procedures, equipment and personnel based on a combination of technical justification (TJ) and test piece trials (open or blind). The TJ is a crucial element in the ENIQ approach, containing evidence justifying that the proposed inspection will meet its objectives in terms of defect detection and sizing capability. A Qualification Body reviews the TJ and the results of any test piece trials and it issues the qualification certificates.

ENIQ has previously conducted a pilot study to assess the application of the ENIQ Methodology in practice. The first pilot study was successful but, because the component chosen for the study was an austenitic weld, could not fully explore the use of technical justifications. This is because techniques such as mathematical modelling, at the time of the study, tended to be applicable only to isotropic materials. Assessment of the inspectability of austenitic welds usually requires the use of test pieces with the same metallurgical structure. Accordingly, ENIQ decided to conduct a second pilot study using a ferritic BWR-type nozzle to shell weld as the subject of the study. A full-scale test piece containing artificially inserted defects was produced to simulate the real component. A specification of the defects, which the inspection is required to find, was drawn up and an inspection was designed to detect and size them.

The objective of the second pilot study was to show how to fully exploit the potential of technical justifications in the qualification of inspection procedures and thereby reduce the number of test piece trials on full-scale components. A second objective was to show how, and under what conditions, existing qualifications can be extended to other, similar components using technical justifications and so minimise the need for additional test piece trials. In the event, resource limitations meant that the second objective could not be attempted. In addition, the first objective was curtailed so that only detection aspects were included and not sizing. Also, lack of resources or time limitations prevented a number of measures that would normally be taken in producing a technical justification such as parametric studies of the influence of cladding. Nevertheless, a technical justification was produced which predicted whether the designated inspection would be successful in detecting the specified range of defects in the test piece which simulated the actual BWR component. This was done without using any information about the specific defects in the test piece since this information is not available in a real inspection. In this report, the predictions are compared with experimental measurements of the test piece defect responses.

In addition, as a separate exercise, three different mathematical models were used to predict the responses of the defects in the test piece to provide information on model applicability and accuracy of prediction. The models are not identified at the request of their developers but the comparison between the observed and predicted responses of the defects in the test piece throws light on the application of models in qualification.

Following all experimental and modelling work, some of the defects in the test piece were destructively examined. This showed that the methods used to incorporate them produced defects with parameters very close to the specified values.

The second pilot study has been largely successful in showing that technical justifications have the potential to predict the outcome of specific inspections and so reduce or remove the need for large scale test pieces in qualification. Resource restrictions prevented parametric studies from being applied as fully as in a real qualification but the technical justification has shown that data from studies reported in the literature can provide valuable information very cost-effectively. If such studies are used, checks must be made that the essential parameter values mean the work is relevant. The pilot study has identified the information required in a technical justification and this is included in the one written where it is available. Where resource or time limitations have prevented the production of the information, the technical justification indicates what is needed.

The pilot study has shown that models are available which give largely conservative predictions of defect response when used within their regimes of validity and has illustrated the importance of ensuring that all models used in technical justifications should be experimentally validated.

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1. Introduction

The first ENIQ pilot study was highly successful in demonstrating the feasibility of the ENIQ methodology[1] for qualification of a specific ultrasonic inspection. However, because the first pilot study involved an austenitic component, the use made of technical justification was not as extensive as might be possible for ferritic components. The third conclusion of the final report of the first ENIQ pilot study[2] was "Further work is needed to explore the use of technical justifications in areas such as the use of modelling and parametric studies to reduce the number of full-scale test pieces in qualification." Consequently, the ENIQ Steering Committee decided to conduct a second ENIQ pilot study on a ferritic component. The detailed objectives were then developed by the Task Group for Qualification, TGQ (formerly TG 2.2), together with a series of steps which would be followed to achieve them, and a proposal was prepared. This was considered by the Steering Committee at its meeting in Prague in June 2000 and received their approval. The component chosen for the study was a clad ferritic BWR-type nozzle-to-shell weld and it was to be inspected from its inner, clad surface.

TGQ produced a detailed method of working[3] and this was adopted to control the conduct of the pilot study. Inspections were made on the test piece chosen for the project and modelling studies were also carried out. The test piece replicated the chosen BWR nozzle weld and its inspection was the equivalent for the pilot study of an actual ISI on a real component. As the project progressed, it became clear that resources for the completion of the pilot study were limited, whether financial or contributions in kind from ENIQ members. These constraints restricted severely the extent to which the original objectives of the pilot study could be achieved. Also, from the perspective of assessing the efficacy of modelling, only a limited number of the responses from the defects in the test piece could be modelled within the range of relevance of the different models offered by participants in the project.

This difficulty was discussed by the Steering Committee at its meeting in Hamburg in June 2004 and it was decided that further inspections should be carried out, this time from the outside of the test piece. This would provide additional defect responses which were susceptible to modelling. Once these inspections were complete, a number of the responses were selected for modelling, ensuring that the measurement parameters were such that the models could be applied. A further requirement determined by the Steering Committee was that the project should be completed by December 2005.

The additional technical requirements outlined above together with the required completion date meant that the method of working and programme originally envisaged required significant modification at an interim stage in the project[4]. A new inspection procedure was needed and new measurements had to be made.

Section 2 contains a description of the project and the way it was organised. This section also discusses the changes that were made in the light of the problems mentioned above. Section 3 describes the measurements and predictions that were made. The outcome of the different parts of the pilot study is discussed in Section 4 and Section 5 identifies the lessons learned. Finally, Section 6 contains the conclusions drawn from the project.

2. Pilot Study Method of Working, Documentation and Organisation

2.1 Method of Working and Changes During the Project

As discussed above, the initial general objective of the 2nd pilot study was to investigate and demonstrate the ability to use technical justifications to reduce the need for test pieces in carrying out qualification. Specifically:

- To show how to fully exploit the potential of technical justifications in the qualification of inspection procedures and thereby reduce the number of test piece trials on full-scale components.

- To show how, and under what conditions, existing qualifications can be extended to other, similar components using technical justifications and so minimise the need for additional test piece trials.

The first objective above was to be attained by producing a technical justification in which the worst case defects for the designated inspection procedure from amongst those in the defect specification would be identified and their responses predicted. If the predicted response levels exceeded the evaluation levels set in the inspection procedure it could be argued that all other defects would be detected because the ones in the TJ were the worst cases. The predictions of the TJ for detection and size measurement would be compared with measurements made on a full scale test piece containing deliberately introduced defects replicating the BWR nozzle to shell weld chosen as the subject of the pilot study. In this way it was hoped to show that full-scale test pieces are unnecessary to qualify such an inspection.

The second objective was abandoned when it became obvious that available resources and the time available were barely adequate to achieve even the first objective. The limitation in resources also meant that the first objective was modified to exclude size measurement and limited to defect detection only. Also, certain steps in achieving the modified first objective were either not carried out or done in a way, which fell short of what was initially intended. For example, it was planned originally to determine the responses of defects in two ways depending on their position. For deeply buried defects, it was planned to use mathematical modelling. For defects nearer the surface a combination of modelling and experimental results from small test pieces was intended. Due to uncertainties in the applicability of the models for defects in the near field, the principal source of information would have to be experimental data. Unfortunately, the resources available to provide experimental studies of near-surface defect response were insufficient to allow the work to be done. Some of the results from surface defects in the unclad test piece were therefore used to partially redress this problem.

Another limitation was that full studies of the effect of cladding on defect response were not possible and only a partial study was carried out. This involved assessing only one of the many beams used in the inspection, propagating in only one direction relative to the cladding direction.

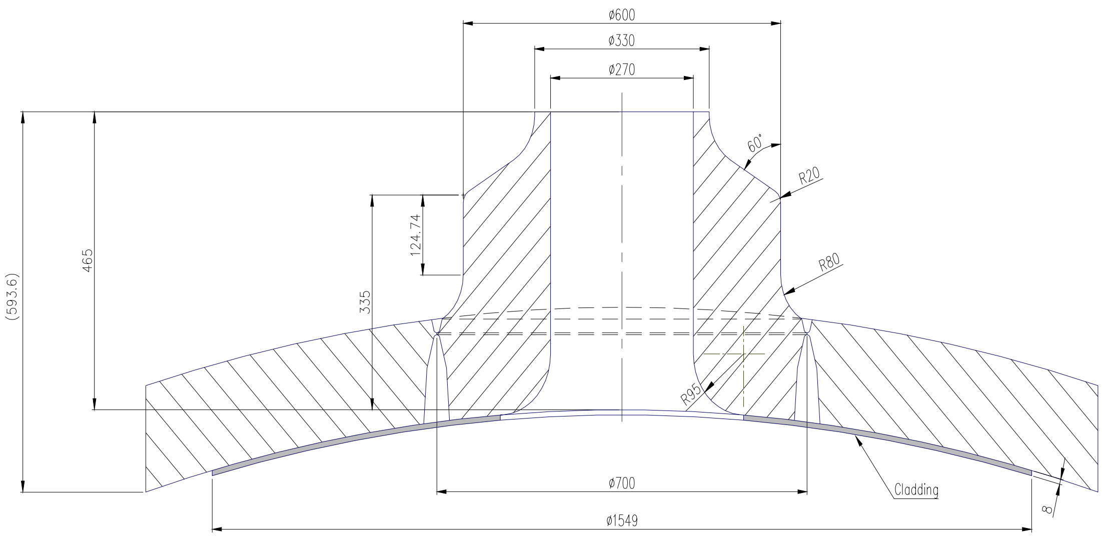
In spite of the limited information available as discussed above, TGQ determined that a technical justification should be produced for the inside clad inspection to illustrate the form that such a document would take for an inspection such as the present one. The TJ would include all information available and indicate, where information was not available, what would normally be included.

In addition to producing a TJ as discussed above, it was determined that the accuracy of available models would be assessed in a separate exercise by applying them to the defects in the test piece and comparing their predictions with experimental measurements. This would not normally be possible in qualification because it requires specific knowledge of defect parameters. In qualification, as discussed above, only the worst-case defects with parameters identified by the TJ are normally modelled. The problem was that the number of defects in the test piece to which the available models could be applied were sufficiently few that further responses were needed if a reasonable demonstration of the efficacy of modelling was to be provided. This was why additional measurements were made from the outside surface of the test piece.

After all measurements had been completed, the test piece was destructively examined to determine the actual parameters of the defects that had been included. This met two objectives. In the first place, it was possible to see how close the parameters assumed for modelling purposes were to the actual ones. Any major discrepancies would influence the relevance of the modelling predictions. Secondly, comparison of the intended and actual parameters gives information on the potential errors made when including defects in test pieces. Such information is relevant to all qualification work carried out using test pieces containing deliberately included defects.

2.2 Component Involved

The component chosen for the pilot study was a ferritic nozzle to shell weld resembling those found in the reactor pressure vessels of BWRs as shown in Figure 1. In what follows, the clad surface of the test piece is referred to as the inner or inside surface because it corresponds to what would be the inside surface of a real pressure vessel. The other surface of the shell is referred to as the outer or outside surface for the same reason. The plate representing the RPV shell was initially unclad. When the nozzle was welded in place, coupons were placed on the fusion faces prior to welding to simulate lack of fusion defects. After completion of welding, spark-eroded slots with sharp tips were introduced on the inside weld surface. The shell plate was then clad using a 2-layer strip process with the strips parallel to what would be the axial direction in a real vessel. This does not correlate with the normal direction in a real vessel and was chosen to simplify the fabrication of the test piece. It does not affect the outcome of the pilot study because defects were inserted around the circumference of the weld so that inspecting probes were scanned over the full range of angles with



Vessel diameter	Inner radius	Weld prep. angle	Shell thickn.	Nozzle diam.	Shell weld diam.	Nozzle surface to shell weld centre
~6400	95	4	~160	270	700	215

Figure 1 – Diagram of the nozzle showing dimensions (in mm)

the cladding. Finally, spark-eroded notches were introduced into the surface of the cladding over the nozzle weld. The clad surface was hand ground after welding. Further details of the defects are given below.

2.3 Defects

The defect specification was as follows:

- Inspection volume is the third of the material nearest the inside surface in either the weld or heat-affected zone which is 10mm on either side of the weld fusion line
- All defects are smooth with surface roughness less than 6.3 µm Ra
- Lack of fusion defects are on the fusion lines and are tilted at the same angle with zero skew
- Cracks at the surface or cladding interface are tilted up to ±20º from normal to the surface and skewed up to ±5º from the weld run direction
- The qualification defect size is 15mm in through wall extent and 30mm long

The defects that were inserted into the test piece are listed in Table 1. Some defects smaller than the qualification size were included to explore inspection sensitivity at lower sizes. As outlined above, the inserted defects were in three groups:

Surface-breaking cracks: These are defects at the inside surface of the test piece over the nozzle weld having their tips either in the cladding or in the weld material underneath. They were produced by spark erosion using an electrode with a sharp tip and have tip radii of less than 40µm. These are so-called PISC type A defects.

Near-surface cracks: These are defects produced by the same process as that above that were surface-breaking prior to cladding. They therefore simulate cracks growing from the cladding interface.

Lack of side-wall fusion defects: these are the defects associated with the coupons on the fusion faces. They are oriented at the fusion face angle and are all embedded.

No.	Type of defect	Fabrication technique	Height [mm]	Length [mm]	Ligament [mm]	Position	Tilt [deg]	Skew [deg]
1	Near surface crack	PISC type A defects	5	20	8	Centreline	0	0
2	Surface crack		5	20	0	Centreline	0	0
3	Surface crack		5	20	0	Centreline	10	5
4	Surface crack		10	30	0	Centreline	10	0
5	Surface crack		10	30	0	Centreline	0	0
6	Surface crack		15	60	0	Centreline	0	5
7	Surface crack		15	60	0	Centreline	20	5
8	Near surface crack		5	20	8	Centreline	10	5
9	Near surface crack		10	40	8	Fusion line	4	0
10	Near surface crack		10	40	8	Fusion line	20	5
11	Near surface crack		15	60	8	Fusion line	10	0
12	Near surface crack		15	60	8	Fusion line	0	5
13	Side wall lack of	Coupon technique	10	20	10	Fusion line	4	0
14	Side wall lack of		15	30	20	Fusion line	4	0
15	Side wall lack of		15	30	30	Fusion line	4	0
16	Side wall lack of		5	50	10	Fusion line	4	0
17	Side wall lack of		5	60	15	Fusion line	4	0

Table 1 – Test piece defects

2.4 Inspection Procedure

2.4.1 General

Inspection procedures were developed for both inside and outside inspections[(5)(6)]. In both cases, the pilot study was restricted to detection of defects.

For the inside inspection, the same procedure was used for the un-clad and the clad test piece. The only difference was that scans additional to the one carried out in the unclad case were carried out at higher sensitivity in the clad case. This was so that any drop in response due to cladding would not lead to unobserved defect signals. Also, 45º pulse echo shear wave probes were not used for the clad inspection because the unclad inspection had shown them to be ineffective. This was also confirmed by the predictions made in Section 6.2 of the TJ. Whenever the response exceeded 100% full screen height and was saturated, the gain was reduced by 3 or 6dB to allow a measurement of response to be made. Essential elements of the procedure are given in Tables 2 and 3 below. Depths are shown from the inspection surface.

The procedure used for outside inspection is summarised in Tables 4 and 5 below. As discussed above, the outside inspection was used simply to generate data for comparison with modelling results. Depths are shown from the inspection surface.

Probe Type	Angle	Frequency	Crystal Size	Nominal Depth Range
Single Crystal Shear	45º	1.5 MHz	32x25mm	20 – 60 mm
Single Crystal Shear	60º	1.5 MHz	32x21 mm	20 – 60 mm
Single Crystal Shear	70º	1.5 MHz	32x18 mm	20 – 60 mm
Tandem Shear	45º	1.5 MHz	32x25mm	20 – 60 mm
Twin Crystal Compression (TRL)	70º	2 MHz	2x(25x15 mm) Focal Depth 12mm	0 – 20 mm
Twin Crystal Compression (TRL)	70º	2 MHz	2x(18 mm ø) Focal Depth 8mm	0 – 20mm

Table 2 – Probes used for inspection from the inner surface

Probe	Reference Reflector/Use of DAC (SDHs)	Calibration Sensitivity	Inspection Sensitivity – Unclad	Inspection Sensitivity – Clad
45º Shear	6.4 mm diam DAC used	80% Full Screen Height (FSH)	Calibration + 6dB	not used for clad inspection
60º Shear	6.4 mm diam DAC used	80% FSH	Calibration + 6dB	• Calibration + 6dB • Calibration + 15dB
70º Shear	6.4 mm diam DAC used	80% FSH	Calibration + 6dB	• Calibration • Calibration + 12dB
45º Tandem	8mm diam at 40mm depth No DAC used	80% FSH	Calibration + 6dB	• Calibration + 6dB • Calibration + 15dB • Calibration + 21dB
70º TRL (fd 12mm)	3.2mm diam DAC used	80% FSH	Calibration + 6dB	• Calibration + 6dB • Calibration + 12dB
70º TRL (fd 8mm)	3.2mm diam at 5mm depth No DAC used	80% FSH	Calibration + 6dB	• Calibration + 6dB • Calibration + 12dB

Table 3 – Sensitivity used for inside inspection

Probe Type	Angle	Frequency	Crystal Size	Nominal Depth Range
Single Crystal Shear	45º	1.5 MHz	32x25 mm	112 – 168 mm
Single Crystal Shear	60º	1.5 MHz	32x21 mm	112 – 168 mm
Tandem Shear	45º	1.5 MHz	32x25 mm	112 – 168 mm

Table 4 – Probes used for inspection from the outer surface

Probe	Reference Reflector	Calibration Sensitivity	Inspection Sensitivity
45º Shear	8mm diam DAC	80% FSH	Calibration + 6dB
60º Shear	8mm diam DAC	80% FSH	Calibration + 6dB
45º Tandem	8mm diam at 125mm depth	80% FSH	Calibration + 7.5dB

Table 5 – Sensitivity used for outside inspection

2.4.2 Defect Evaluation Level

The defect evaluation level is designated in the procedure as when indications exceed 20% FSH (12dB down on the reference reflector/DAC response) on three successive scan lines for shear waves, including tandem, and 40% FSH (6dB down on the reference reflector/DAC response) on three successive scan lines for compression waves. Originally, it was planned to evaluate signals only when they exceeded these levels. However, when resource limitations prevented an accurate assessment of the effect of the cladding, signals were recorded at lower levels. This was because an accurate compensation for losses due to cladding was not available. Consequently it was unclear whether a particular defect signal in the clad block would have been above or below an evaluation level determined using measurements of cladding losses had these been available. This level will continue to be referred to as the evaluation level in the remainder of this report but it should be understood that signals lower than this level were recorded for comparison with modelling predictions. In the event, the assessment of defect sizing was abandoned because of resource limitations and so the significance of the evaluation level as a way of identifying candidates for size measurement disappeared.

2.5 Production of Controlling Documents

Unlike the first pilot study, the present exercise was not conducted as a qualification. The intent was to generate information to achieve the two objectives set out in Section 2.1 above. No blind trials were involved and all inspections of the test piece used to simulate a real ISI were carried out by personnel with a knowledge of the defects within the test piece. The only aspect of the study which was carried out blind was the modelling. So far as possible, all information about defect responses from the test piece was kept secret from the modellers until their predictions had been made. This was not possible in every case because some modelling was carried out after the results were available.

Because of the above, no qualification procedure was necessary. It was also unnecessary for the roles of the various parties in qualification such as the utility, regulator, vendor, qualification body etc. to be simulated as was done for the first pilot study.

The quality of the work carried out was controlled through a quality assurance programme produced by the JRC[(7)]. This includes the above confidentiality requirements for modelling. The overall strategy for the pilot study and the means for achieving it were set out in a Method of Working document[(3)(4)], which was updated as the project developed and its objectives were reviewed. Minutes of ENIQ Task Group – Qualification (TGQ) meetings also record the decisions that were taken.

3. Conduct of the Pilot Study

3.1 Inspections of the Test Piece

The test piece was inspected three times. The first inspection was when the block was unclad and was carried out from the inside surface. Consequently, there are no results from the defects inserted later into the cladding. This inspection was done by JRC/WesDyne TRC AB[(8)].

The second inspection, also by JRC/WesDyne TRC AB, was from the outside surface after the block had been clad and the report of the inspection includes results from all defects[(9)].

The final inspection was of the clad block from the inside surface and this inspection was carried out by the JRC[(10)]. Circulation of the inspection results was restricted until after the TJ was produced.

3.2 Use of Modelling

Normally, modelling is carried out as part of a technical justification. Analysis of the inspection and its objectives is used to identify those defects from the defect specification which are most difficult for the proposed inspection to detect. This may be because of their size, position, orientation or surface morphology. These are known as the "worst case defects" for detection and there may be several of them depending on the reasons why they are difficult to detect. Once the worst case defects have been identified, modelling can be used to predict their response to the ultrasonic inspection if their parameters are within the range of validity of the model. If their response exceeds the stipulated recording level, the defects can be detected and since they are worst case defects, all other defects from those in the defect specification can also be detected.

In the 2nd pilot study, modelling was carried out as part of producing the TJ in the way discussed above. This is discussed further in Section 3.4 below. However, modelling of certain specific defects in the test piece where the models were considered applicable was also carried out[(11)]. This was done to illustrate the range of applicability of some currently available models. It was also done to give an indication of the likely accuracy and consistency of the predictions of different models by comparing the predictions with the actual measurements. The outcome of this work is discussed in Section 4.2 below.

3.3 Use of Parametric Studies

In some situations modelling may not be possible or may not be very reliable. This situation can arise in the case of austenitic welds where the anisotropic structure of the material may bend and distort the ultrasonic beam in a way which is difficult to predict. In addition, such materials often generate large amplitudes of noise from the grains of the structure and this may prevent detection rather than weak reflection *per se*. Also, the results from models for defects at short ranges may not be reliable because they fall within the near field of the transducer. In such situations, the normal recourse is to use parametric studies to make predictions of defect response. Simple test pieces containing inserted defects are inspected using the stipulated procedure and the amplitudes of response are used to predict those from the actual component. In the case of austenitic welds, test pieces fabricated using the same welding procedure as the actual component may be needed to ensure levels of beam distortion and structural noise are realistic.

Factors such as cladding can also affect amplitudes and this can also be predicted using parametric studies on small test pieces to determine the magnitude of the effect. The results of such cladding parametric studies can be combined either with modelling predictions or with the results observed from the small parametric blocks containing defects discussed above to give an overall prediction of signal response. The general intention of the parametric studies is to avoid the need to produce large test pieces in the first instance but also, if such test pieces have to be produced, to simplify them by avoiding the need for cladding and the need to replicate any other difficult parameter which might affect the outcome of the inspection.

Because it was known that cladding has an effect on the transmission of beams, it was decided to conduct a specific investigation of the influence of the specific cladding type used on the test piece. This is described in reference 12. Unfortunately, the uncertainties discussed above in applying modelling from the inside surface of the test piece meant that effort had to be diverted to carrying out an inspection from the outside surface. This provided additional defect responses for comparison with the model predictions but curtailed the cladding investigation. Consequently, only one probe, a 1.5 MHz 60º shear wave transducer, was studied and then with the beam only in the direction perpendicular to the cladding welding direction. In reality, the inspecting beams assume all orientations relative to the cladding direction because the cladding is parallel to the "vessel" axis and the weld is a circular nozzle weld. The results showed that, in general, cladding had the effect of reducing the transmitted beam amplitude to 60% of its value in a non-clad specimen, a fall of 4.4dB. A larger fall was observed in one probe position but further work suggested that this was due to the surface profile of the parametric block at this position.

3.4 Technical Justification

A technical justification was produced for the pilot study(13). The author of the TJ had no knowledge of the results of the inspection of the full-scale test piece. The TJ was written to illustrate the form that a real TJ might take for this inspection. The arguments that support the first objective of the pilot study, showing that production of a TJ has the ability to reduce the demand for major test pieces, are given in Section 4. The TJ was limited to inspection from the clad inside surface because this is where some parametric studies are available to show how these would be incorporated into a TJ. The TJ lacks some of the information that would normally be included in such a document because of the resource and time constraints noted above. Where this is the case, the TJ identifies the "missing" information and gives comments on what would normally be included in the TJ at each point.

The TJ is structured as in ENIQ Recommended Practice 2(14) and contains an analysis of essential parameters as in ENIQ Recommended Practice 1, Issue 2(15). As recommended in the latter document, the TJ identifies the essential parameters for this inspection and then focuses attention on the ones to which the inspection is most sensitive. Others are dealt with more briefly in a way commensurate with their lesser significance for influencing the outcome of the inspection. The TJ then goes on to identify which of the defects in the defect specification in Section 2.3 above are the most difficult to detect because of their position or orientation. The geometry of the nozzle to shell weld which is a cylinder/cylinder intersection also means that circumferential position around the nozzle is also important. Once the worst case defects have been established, their responses are predicted using modelling as discussed in Section 3.2 above. For the purpose of the TJ, one of the three models used to predict the responses of the defects in the nozzle test piece was selected and used in the TJ to illustrate the process. In some cases, the defect lies in the near field of the probes used to detect it and then the models become unreliable as discussed above in Section 3.3. In this situation, experimental data is normally used in place of modelling to predict response. Because the defects for which modelling is least appropriate are at or near the surface in this case, only small test pieces would be needed and these need to be only in simple geometry. This means that it would be very inexpensive and easy to generate data from the actual equipment to be used for the inspection to indicate the level of response to be expected from this type of defect. The TJ also identifies the worst case defects and these can then be incorporated into the parametric blocks, making them more effective in assessing the inspection. In this particular case, the resource limitations discussed elsewhere in this report meant that even these simple blocks could not be produced and so some of the data from the unclad test piece was used in the TJ in place of data from parametric studies blocks to illustrate this process.

Parametric studies data on cladding was very limited as discussed above and so a literature search was made to establish what influence 2-layer strip cladding of the type used in the pilot study had had in other investigations. One of the pieces of work investigated showed that 2-layer strip cladding of the type used here had its greatest effect on high angle (70º) shear waves. The effect on 45º and 60º shear waves at 1.5 MHz was found to be up to 10dB with a standard deviation of 4dB. This was mainly due to the surface form of the cladding and another study on machined cladding showed effects of about 2 to 4dB only. The cladding in this case was hand ground and so the former figure is likely to be applicable to the test piece. No studies on 70º TRL probes could be found. It was therefore assumed that, since the effects appear associated with surface form, the same correction should apply as for other probes.

3.5 Destructive Examination

As discussed in Section 2.1 above, the test piece was destructively examined following completion of all ultrasonic work(16)(17). The fusion face defects were removed from the complete test piece by inserting saw cuts in such a way as to produce a smaller sample containing the defect. The defect was then sectioned at points along its length to reveal its through wall extent, orientation, position, topography and length. Three defects were selected for this work which was done at NRI Rez in the Czech Republic(16). NRI have also made estimates of the depth to which cladding will penetrate into the defects placed in the surface of the unclad test piece.

The surface-breaking defects inserted into the clad and unclad test piece were investigated by JRC using replica techniques(17).

4. Results of the Pilot Study

4.1 Inspection Results

The results obtained from the three inspections of the test piece are summarised in Appendix 1.

4.1.1 Results from the Inside Inspection of the Unclad Test Piece

All the defects in the unclad test piece were detected by at least one of the 70º TRL probes above the evaluation criteria except for defect 1. This was a 5mm x 20mm defect which was detected on only 2 scan lines (instead of the required 3) above the 40% FSH criterion.

No defects were detected with the 45º shear wave probes in pulse echo.

Two defects, 14 and 15 were detected with the 60º shear wave probes.

The 70º shear wave probes detected defects within their inspection range but also generated a high noise level, in some cases exceeding the evaluation level. Because of this, no data from these probes is given in Appendix 1 although where a clear response was obtained, comparison is made with modelling predictions in Appendix 2.

The tandem inspection was effective in detecting all defects except 1 and 10 above the evaluation criteria. Both these defects are surface-breaking.

4.1.2 Results from the Outside Inspection of the Clad Test Piece

All defects were detected by at least one of the probes except for defect 8. This is a 5mm x 20mm defect located at the cladding/weld interface. A large number of false calls was noted, associated both with the clad interface and the weld volume.

4.1.3 Results from the Inside Inspection of the Clad Test Piece

All defects were detected above the evaluation level using the 70º TRL probes except 1, 2 and 3. These are all 5mm x 20mm defects at or near the surface. Defect 1 was detected on 2 scan lines by one of 70º probes in the inspection prior to cladding but the signal from the particular 70º probe was 4.5 dB lower after cladding and so was below the evaluation level.

Two defects were detected by the 60º shear wave probe above the evaluation level. Four defects were detected with the 70º shear probes.

The tandem inspection detected 4 defects above the evaluation level.

4.1.4 Comparison of Results from the Clad and Unclad Inside Inspections

Table 6 below shows the change in response (in dB) for inspections before and after cladding for those defects in the test piece which were present before cladding. A positive value indicates that the signal was higher prior to cladding.

Defect	Probe Scan							Aver-age	St Dev	Av(70)
	60+	60-	45T	70+(12)	70-(12)	70+(8)	70-(8)			
1			11.5	0.8	-0.5	1.1	4.5	**3.5**	4.9	1.5
8				c	-0.5	c	6.6	**3.1**	5.0	3.1
9			18.3	1.1	-4.4	-0.8	-0.5	**2.7**	9.0	-1.2
10				-5.2	-8.1	-2.3	-8.0	**-5.9**	2.7	-5.9
11			11.9	-0.5	-3.6	-1.1	-0.3	**1.3**	6.0	-1.3
12			10.7	3.3	8.5	-1.1	6.3	**5.5**	4.6	4.2
13			6.0	1.4	-0.3	6.4	-3.7	**2.0**	4.3	0.9
14	2.7	7.8	-1.2	3.2	-1.1	u		**2.3**	3.7	1.1
15	7.9	U	11.8	1.2				**7.0**	5.4	1.2
16			15.1	-0.4	-1.8	-3.0	-4.1	**1.2**	7.9	-2.3
17			11.8	7.0	1.2	8.5	6.2	**6.9**	3.9	5.7
Average	**5.3**	**7.8**	**10.7**	**1.1**	**-1.0**	**0.9**	**0.8**			
St Dev	3.7		5.5	3.1	4.3	4.2	5.4			

Table 6 – Comparison of defect responses from the clad and unclad test piece

Note:
1. *The probe scans are designated as – if the beam is directed towards the nozzle and + in the other direction.*
2. *All probes designated 70 are TRL probes, either 12mm focal distance or 8mm as indicated. All others are shear waves. T is tandem.*
3. *Av(70) is the average, for each defect, of all the 70º scans.*
4. *Absence of an entry above indicates that a signal was not seen on both inspections. A "u" indicates that a signal was observed in the unclad inspection but not the clad one, a "c" that one was observed in the clad inspection but not the unclad one.*
5. *St Dev in both cases is the standard deviation about the overall average.*

The table shows that the average change in signal over all the defects for the 70º TRL probes was small although there is some scatter in the data. Average change for the 60º shear probes was greater and, for the tandem, about double the 60º figure.

Averaged over all the detecting probes, most defects show a decrease in signal as a result of cladding. The notable exception is defect 10 which shows a rise in signal after cladding of 5.9dB with a standard deviation of 2.7dB. Defect 10 is a PISC Type A crack at the cladding interface, 10mm in height and was detected by the 70º TRL probes. It is tilted at 20º to be favourably oriented for the 70º probes in the positive beam direction. It is unclear how the cladding could improve such a favourable situation except by placing the defect 8mm or so deeper where the response to the two focussed TRL probes may be enhanced and offset any losses due to cladding. Some other defects also show an average increase in response after cladding for the TRL probes, albeit smaller than for defect 10. These tend to be defects which were originally at or very near the surface and a similar explanation may apply.

The results of the comparison support the conclusion of the TJ that cladding effects for shear wave probes would be about 10(±4) dB for hand ground cladding. However, the comparison also shows that, contrary to the assumption in the TJ, effects for TRL probes are very much smaller. This means that the assumption of the TJ for these probes is a conservative one.

4.2 Modelling

Three different models were used to predict the responses of the defects in the test piece[(11)]. As discussed earlier, the purpose of applying the models was to indicate the type of results produced by a range of models and to illustrate their range of applicability. Those who developed the models made it a condition of their participation that the results would be treated anonymously and details of the models would not be supplied that could be sufficient to identify the models used. Consequently, to preserve anonymity, this report does not contain information about the origin of each model, the principles on which it is founded or who it was applied by. The models are therefore referred to as A, B and C. The modelling predictions for the defects in the test piece are tabulated in Appendix 2. In cases where no modelling prediction is shown, this is either because the particular model is not applicable for this case, or because resource limitations prevented the modellers from modelling all the possible cases. The appendix contains predictions for both inside and outside inspections and compares the predictions with the experimental data. In some cases, the probe/defect parameters are outside the range where the model is expected to be strictly valid and this situation is identified in the tables. There are a limited number of defect/probe combinations where both modelling predictions and measurements above noise levels were possible.

For the outside inspections, two of the models, A and C, were used to make two sets of predictions. Initially, only the signals directly from the defect were predicted. The potentially large signals, which arise via sound reflecting from the defect onto the far surface of the test piece and then back to the probe, the so-called corner effect, were not considered. This was because the far surface of the test piece is clad and it is not possible to predict accurately any reflection from this. It was then realised that omitting such a significant reflection mechanism would lead to large discrepancies between predicted and measured responses. Consequently it was decided to make further calculations including the corner effect as if the far surface were ferritic. This involves uncertainties in the results arising from the reflection from the clad surface but not as great as those, which arise from omitting the corner effect completely. Only these latter calculations are included in this report where both were done because of the major discrepancies in making comparisons, which do not involve the corner effect in the predictions. The other results are given in reference 11. In addition to uncertainties arising from the clad surface as discussed above, there are also problems associated with the geometry of the test piece. These are given in the footnote to the table in Appendix 2.2 and discussed more fully in reference 11.

For the outside inspection, lack of resources prevented model A from being applied for corner effect predictions to the 60º probe and to the 45º probes for defects 10 and 12. The same applies to the application of model C to defects 10 and 12. These are skewed and, while the model could be applied, the process is more time-consuming and resource constraints meant that the work could not be done. It should also be noted that the application of models A and C to the outside inspection including prediction of corner effect took place after the experimental results were available.

The results in Appendix 2 show considerable variations between the models for the same defect and probe even where there are no reservations about the validity of the model as discussed below.

Model A is generally conservative in its predictions for both inside and outside inspections. Only 2 probe/defect interactions had predicted values which exceeded the observations and then only by a slight amount (2dB and 0.4dB). These both relate to outside inspection results where the factors noted in Appendix 2.2 may be responsible. The mean degree of conservatism is about 4.6dB with a standard deviation of 2.4dB for inside inspections and 5.4 dB (standard deviation of 6.6dB) for applications to the outside inspection involving calculations of corner effect. Note that model A could not be applied to the 70º TRL inspections.

Model B in general is highly non-conservative. Excluding the tandem inspections, from the outside only two comparisons between predicted responses and measured ones show a conservative prediction out of 14 comparisons in total. Mean value for difference between prediction and measurement for pulse echo inspections is 7.5dB (standard deviation of 6.2dB). The predictions for the tandem response in the outside inspection tend to be very conservative with 14.6dB mean value and a standard deviation of 7.3dB. For inside inspections, there are no conservative predictions in 8 comparisons (pulse echo and tandem). Mean difference is +15.1dB with a standard deviation of 6.9dB. In addition, model B predicted substantial responses, well above the recording level, for many defect/probe combinations where no defect signal was observed. In summary, therefore, model B gave highly non-conservative results for pulse echo and inside tandem inspections and highly conservative ones for the tandem inspections from the outside surface. Both sets of results showed a high degree of scatter.

In general, model C gives conservative predictions of response. For the inside inspection, the overall mean conservatism is 2.9dB with a standard deviation of 7dB. From the outside, where the corner effect was included the corresponding figures are a mean conservatism of 3.6dB with a standard deviation of 4.2dB.The only probe predictions which are non-conservative are some of those for the 70º TRL probes and those for defect 9 from the outside with the 60º and 45º shear wave probes. The limitations noted in Appendix 2 may be responsible for the latter. The 70º TRL results possibly arise from the use of the model in the near field of the probes. It is notable that results for more deeply embedded defects are more conservative than those for defects nearer the surface with these probes. Where it is possible to make comparisons between them, models A and C agree within about 7dB although for defect 17, the difference with 45º probes is 10.3dB.

Considering the variations noted above between the predictions of the models and the data from the test piece, it is crucial that any model used in practice in TJs is experimentally verified. Such verification would give confidence in the use of the model, confirm any limitations in the applicability of the model and provide guidance on the degree of conservatism involved. When used in a TJ, references should be given to the documents, which describe how the model was verified. From the above comparisons, it is possible to say that both models A and C could be used with confidence in a TJ to make useful, conservative predictions of defect response. In the very few cases where the predictions are not conservative the margin is very small, being at most 1.9dB for model A and 3.4dB (excluding the TRL probe predictions) for Model C. These non-conservatisms occur for inspection from the outside surface using the corner effect, and may arise from approximations made in this particular application. The same claim for conservatism could not made for model B where the discrepancies between prediction and measurement are large and usually non-conservative.

4.3 Technical Justification

As discussed in Section 3.4, the TJ identifies the defects from those in the defect specification, which are most difficult to detect from the inner clad surface because of their position and orientation. A geometric model, which determines the misorientation between the defect and the different probe beams in the procedure, is used to make the assessment. The model takes account of the saddle geometry of the nozzle weld to identify the azimuthal positions, which are most difficult. At the qualification size, 15mm x 30mm, the worst case defects are as follows:

- Surface-breaking or underclad cracks which are normal to the local surface and skewed at 5º
- A near-surface lack of fusion on the shell-side fusion face at 60º azimuth
- A lack of fusion defect at maximum depth on the shell-side fusion face at 90º azimuth

Once the worst case defects have been identified, a model which predicts defect response was used to determine whether they and other similar defects of qualification size would be detectable at the sensitivity used to evaluate them. The model used was one of the three involved in the predictions discussed in Section 4.2 above. It was chosen because it was easiest to apply for logistical and resource availability reasons. Table 7 below shows the defects that were modelled and Table 8 shows their predicted responses with the worst case defects (2, 7 and 9) shown shaded. The responses are shown in dB above the evaluation level. The absence of an entry in Table 8 means that no modelling was done for this probe/defect combination. It should also be noted that the numbers allocated to each defect in the TJ are uncorrelated with those shown in Table 1 for the different defects in the full-scale test piece.

No	Azimuth	Depth (mm)	Location	Tilt (°)	Skew (°)	Beam angles
1	60	0	Weld Centreline	0	0	70 TRL
2	**60**	**0**	**Weld Centreline**	**0**	**5**	**70 TRL**
3	60	8	Nozzle side HAZ	0	0	70 TRL
4	60	8	Nozzle side HAZ	-5	0	60, 70 TRL
5	60	8	Nozzle side HAZ	-10	5	60, 70 TRL
6	60	10	Nozzle side fusion face	-4	0	Tandem
7	**60**	**10**	**Shell side fusion face**	**+4**	**0**	**Tandem**
8	90	40	Nozzle side fusion face	-4	0	Tandem
9	**90**	**40**	**Shell side fusion face**	**+4**	**0**	**Tandem**
10	60	40	Shell side fusion face	+4	0	Tandem
11*	60	10	Shell side fusion face	+4	5	Tandem

Table 7 – Defects modelled for the TJ

* *Note this defect is outside the defect specification but has been included to show the effect of skew on a near surface defect*

Defect	Tandem 45°	60° shear	70° shear	70° TRL
1				-4.2
2				-7.2
3				-1.1
4		-0.6	1.4	1.1
5		1.7	4.4	1.4
6	16.5			
7	15.8			
8	41.8			
9	32.8			
10	33.7			
11	15.4			

Table 8 – Modelling results from the TJ (dB relative to reporting threshold)

No significant responses were predicted for the 45° shear wave pulse echo probes and so these are not included in the table. The above results also include no correction for any losses that might result from the cladding. Determination of cladding corrections is discussed in the TJ and in 3.4 above.

The results show that lack of sidewall fusion defects (6 to 10) should be readily detected at all depths using the tandem inspection.

For underclad defects nearer the surface (3 to 5), the 70° TRL probes and the 60° and 70° shear pulse echo probes provide responses at best only just above the evaluation level. Qualification size defects at the surface which are untilted (1 and 2) are predicted to remain undetected, especially when skewed. Had this been a real qualification, these results may have led to a decrease in the evaluation level, within the limits allowed by noise signals, to provide for more certain detection. Another consideration is that the model is only strictly valid in the far field and so may give inaccurate results for near surface and surface defects. This is why the response from surface and near-surface defects is normally determined by parametric studies. Because the defects are near the surface, the blocks will be small and geometrically simple and the responses of the defects they contain can be determined using the same probe types that will be used for the actual inspection. Resource limitations prevented such work from being done for the pilot study but an attempt was made in the TJ to use data from the unclad block as a substitute for the simple parametric studies outlined above. This data and no other was released to the TJ author for this purpose. The discussion of this data in the TJ indicates that the modelling data is indeed conservative. Further evidence of this is provided by defect 12 in the main test piece. This is a 15mm deep defect, tilted at 0° and skewed at 5° and represents the worst case for surface breaking defects. Appendix 1.1 shows that the response of this defect is such that it is readily detected by several of the 70° TRL probe scans. Even when the test piece is clad it is still detected by one of the TRL probes at about 4dB above the evaluation level. This demonstrates that, had data of this kind been available to the author of the TJ through parametric studies to complement the modelling in areas where it is not strictly valid, there would have been no difficulty making the case that all qualification size defects would be detected.

The conclusion of the TJ is that "…*based upon consideration of physical reasoning, theoretical modelling, parametric studies and documented previous experience, that the inspection procedure under consideration, provided it is properly implemented by suitably qualified and experienced personnel, is capable of detecting all defects in the ferritic part of nozzle assembly 21 that meet or exceed the qualification defect specification, but that reliability could be improved by optimising the tandem setting and by increasing the sensitivity of the near surface inspections.*

The claimed performance relies heavily upon the predicted capability of a single tandem probe set-up. As there is some uncertainty regarding the validity of the calculation performed it is recommended that empirical confirmation of the predicted performance is sought using simplified test blocks, at least one of which should be clad with 2 layer strip cladding and include skewed surface breaking defects.

The capability for detecting all surface breaking and underclad defects of qualification size through the use of 70° TRL probes cannot be fully justified. Defects with tilt angles between 10° and 20°, with or without skew and unskewed defects with tilt between 5° and 10° should be detected, although the evidence is not extensive. However, defects orientated perpendicular to the inspection surface are predicted to give a response below the reporting threshold, and even though it is likely that such flaws will be detected by the tandem probe inspection, it is recommended that empirical trials be performed to determine the actual capability for such flaws."

4.4 Destructive Examination

As discussed in Section 3.5 above, three of the lack of fusion defects were investigated by removing them in smaller samples from the test piece and then sectioning them along their length to reveal their size, orientation, position and character. The surface breaking defects were investigated using replication and also estimates were made of the extent of penetration of cladding into the near surface defects, which were surface breaking prior to cladding.

4.4.1 Lack of Fusion Defects

The three lack of fusion defects chosen for sectioning were 13, 16 and 17. The results are summarised in Table 9 below.

Defect	Through Wall Extent (mm)		Length (mm)		Tilt		Ligament (mm)	
	Measured	Intended	Measured	Intended	Measured	Intended	Measured	Intended
13	11.49, 11.08, 10.3, 10.9	10	19.2, 19.6	20	3.15º, 2.65º, 3.6º	4º	10.88, 10.97, 11.2, 10.9	10
Average	10.9		19.4		3.14º		11.0	
16	5.6, 5.2, 5.3, 5.3	5	48.4	50	5.4º, 6.25º, 6.85º	4º	11.7, 12.1, 11.8, 11.7	10
Average	5.4		48.4		6.2º		11.8	
17	5.8, 5.8, 5.5, 6.4	5	59, 61	60	2.85º, 2.4º, 2.05º	4º	14.7, 14.8, 14.2, 13.7	15
Average	5.9		60		2.4º		14.4	

Table 9 – Results of the destructive examination of LOF defects 13, 16 and 17

It can be seen from the above that average defect through-wall sizes were within 1mm of those specified and average defect lengths within 2mm. Defect ligament for Defect 16 was 1.8mm different on average but the average discrepancy was within 1mm for the other two defects. Average defect tilt was 2.2º away from the expected value of 4º for defect 16 but less for the other two. Examination of the micrographs of the defect tips (16) shows that the increased sizes of the defects over those intended arises from small extensions beyond the end of the plate inserted to generate the primary lack of fusion. The defect tips are sometimes rounded rather than sharp.

4.4.2 Surface and Near Surface Defects

All surface and near surface defects were inserted by spark erosion using electrodes shaped to produce sharp tips – so called PISC Type A defects. Replicas were taken of the near surface defects before cladding, i.e. when they were still surface breaking. Measurements on these(17) show that sizes were very close to those intended. The maximum departure from intended sizes was found for defect 10. The value of the difference for both length and through-wall extent was 1mm, making the defect smaller by this amount in both dimensions. It is estimated by NRI Rez based on their experience that cladding of the type used here might penetrate about 1.5mm into the crack and would therefore reduce through wall sizes by this amount(16). JRC has found reductions of 1mm in the past. In this particular case wedges were placed in the defects prior to cladding to prevent penetration and so the reduction of size will be between zero if there was no penetration and about 1.5mm if the wedges were ineffective.

The opening angle of the defects was about 12-15º, making the tilt of each face of the defect differs by 6-7.5º from the intended tilt. Crack tip radii were found to be very small.

5. Discussion

5.1 Introduction

The first objective of the pilot study was to examine the value of TJs in reducing the need for large, realistic test pieces in qualification. These are expensive and can introduce delays because of the time needed to fabricate them. The features of such test pieces which lead to the problems are their size, the need for them to replicate sometimes complex geometry, the fact that they may need to be clad and the need for them to contain large numbers of defects covering the parameter ranges of the defects in the defect specification.

The TJ produced as part of the pilot study has shown how to use modelling to avoid some of the need for test pieces. Use of physical reasoning for simple cases can determine which of the defects in the defect specification are most difficult for the inspection procedure to detect and size – the worst case defects. This is on the basis of:

- their orientation to the different beams used in the inspection
- their position in the component and the ease with which they can be insonified
- their roughness
- their size if this is affected by their position

In more complicated geometries, models to predict angles of incidence may simplify assessment of this aspect of determining the most difficult defects. Such a model was used here because of the saddle geometry of the nozzle weld and the fact that angles of incidence depend on azimuthal position around the nozzle.

Once the worst case defects have been identified, models which predict defect response can be used to determine whether signals from the defect would exceed the specified recording level.

5.2 Predictions for Embedded Worst Case Defects

Using the approach above, it was predicted that, for worst-case defects at 10mm ligament and deeper, the tandem inspection would produce signals very significantly above the recording level with margins exceeding 15dB (Table 8). For the unclad test piece, the prediction that the tandem technique would generate large signals was accurate. For defects with a ligament of about 10-12mm, the predicted response was very close to that observed from defect 14 in the test piece. This was a 15mm lack of sidewall fusion defect with a ligament of 12mm. In practice, some of the shear wave pulse echo probes and the 70º TRL probes also detected this defect. At a lower recording level, even larger numbers of probes would have detected defect 14. This illustrates the point that, during qualification, the work may identify weaknesses in the initial inspection procedure and ways in which it can be improved. In a real qualification, the procedure would be modified to take such points into account and the modified procedure would then become the subject of the qualification. This is why there is a risk in carrying out inspections prior to qualification, as often happens because of operational pressures.

A key conclusion from the above discussion is that, for embedded defects, the modelling predictions are conservative. A prediction that worst case defects will be detected gives confidence that all other defects with more favourable parameters would be detected. Only if the modelling predicted non-detection would it be necessary to take further steps. This might then involve the production of test pieces to determine defect response.

5.3 Predictions for Surface-Breaking and Near Surface Worst Case Defects

The above discussion relates to embedded defects. For surface-breaking and near-surface defects the situation is different. Models to predict defect response are often not strictly valid in the near field of the probes. This means that any predictions for defects at short ranges, for example near-surface defects, are unreliable. The discussion on modelling in Section 4.2 above, for example, concluded that model C sometimes produced non-conservative results for the 70º TRL probes for such defects where it was possible to make comparisons with measurements. The preferred way to determine the response of near-surface defects is to produce small test pieces containing such defects and to make direct measurements using the same probes and equipment as for the actual inspection. Because the defects are at or near the surface, the test pieces will be small and easily fabricated. They will also be simple because it will not usually be necessary to simulate any complex geometry since, at short ranges, geometry has only minimal effect on the inspection. As mentioned throughout this report, resource limitations prevented the production of such test pieces. However, results from the unclad test piece simulating the actual component illustrate the benefits of this approach. A worst-case surface-breaking defect is one, which is untilted and skewed at 5º, the maximum allowed by the defect specification. The modelling in the TJ predicted that such a defect would not be detected at the specified recording level. However results from defect 12 in the full scale unclad test piece showed that detection is possible by both the tandem inspection and three of the 70º TRL scans. A small test piece containing such a defect would have demonstrated that the 70º TRL scans in the procedure were adequate for such defects, albeit with small margins at the specified evaluation level. Signal to noise ratios were sufficiently high that the recording sensitivity could have been increased to improve margins. This is a further illustration of the way in which the TJ could be used to identify weaknesses and improve inspection performance prior to application in earnest.

5.4 The Influence of Cladding

Another feature of the inspection, which is included in the TJ, is the influence of cladding. If the magnitude of this influence can be determined through parametric studies, allowances for it can be made when predicting defect response using either models or small blocks as discussed above. This also avoids the need, should test pieces be required, to have them clad. This was another investigation, which was curtailed by resource problems, and so the TJ investigated the outcome of other studies, which have been made on cladding effects. In doing this it was necessary to verify that the ultrasonic parameters investigated were relevant to the present situation in terms of probe types, frequencies etc. Using this approach, the TJ determined the likely magnitude of cladding effects. These predictions were verified as giving an accurate assessment by comparing them with the measurements on the test piece before and after cladding as discussed in Section 4.1 above. This illustrates the benefit of reviewing the literature for relevant information, which might avoid the need to do some of the parametric work.

5.5 Defect Roughness

The defects in the pilot study were smooth and so modelling, or smooth defects in parametric test pieces, could be used without the need for a correction for defect roughness. Smooth defects reflect sound strongly under specular conditions but the response falls quickly away from the specular direction. When smooth defects are substantially misoriented they are detected through the weaker signals from their edges, which are diffracted over wide angles. The effect of roughness is to weaken the specular response but to improve the reflection away from the specular direction. Rough defects can therefore be detected over a range of angles although the test sensitivity must be often be increased to cope with the reduced signal level. Defect surface roughness begins to have an effect on the ultrasonic response when the surface undulations exceed about 0.1λ, where λ is the ultrasonic wavelength. In this case, surface roughness of the defects is 6.3 μm Ra and so they are smooth on the scale of the wavelength.

When defects are rough, it is necessary to make corrections for the roughness when constructing a TJ. Models, which include the effects of roughness, are not widely available. It is also very difficult to fabricate rough defects in test pieces with any degree of realism. Consequently, corrections to predicted or observed responses must be made on the basis of laboratory studies, which have determined the magnitude of the effect of roughness under a range of conditions(18). This allows a TJ to be produced when some or all the defects in the defect specification are rough on the scale of the ultrasonic wavelength.

5.6 Destructive Examination

As discussed above, destructive examination has shown that the defects incorporated into the test piece had sizes, positions and orientations very close to those which were specified. Average through-wall sizes were within 1mm of intended values. The surface defects tended to be smaller in through wall extent than assumed and the embedded defects larger. Penetration of cladding into the near surface defects may have reduced their through wall extent by a further 1 to 1.5mm. Ligaments for the embedded defects were within 2mm of those specified. The particular method used to incorporate surface defects means that defect faces were about 12 to 15º to each other rather than being parallel. Thus the tilts of each face were about 6 – 7.5º either side of the intended tilt. Average orientations for embedded defects were within 2.5º of the expected value.

Two conclusions arise from this data:

1. The methods used to incorporate the defects used here into the test piece produced defects with parameters very close to those which were specified. This means that such methods of defect incorporation can be used with confidence to produce test pieces for qualification without the need for destructive examination to confirm defect parameters. This gives the test pieces a longevity which would not be possible unless there were confidence in the defect sizes.

2. The differences between the actual defect parameters and the specified values which were used in the modelling calculations are sufficiently small that the conclusions reached in Section 4.2 above about the value of models are unaffected:

2.1 For the embedded lack of fusion defects, where defect sizes are bigger than those assumed, the sizes used in modelling should have been slightly larger and this may have slightly increased the predicted response in some cases. The effect of this would have been to diminish slightly the pessimism shown in Tables 2.1 and 2.2 in Appendix 2 for such defects. The slight differences between the intended and actual tilts (up to 2.2º) will also have a small effect on the predicted ultrasonic responses.

2.2 It is not so easy to see how the differences in the parameters of the surface and near surface defects would have affected the reported pessimisms. There are small differences in size from the assumed values, but also the defect tips of the PISC Type A defects have a different morphology (defect faces at 12 - 15º to each other) from those modelled (parallel defect faces). The consequence of this latter difference is hard to quantify, but is likely to be small and to have little effect on the conclusions regarding surface and near surface defects.

5.7 Summary

The discussion above indicates the way in which the pilot study has shown how a TJ can avoid the need for large test pieces.

To do this a TJ would typically include:

- An assessment of the essential parameters for the inspection
- Physical reasoning to identify probe/defect angles of incidence in simple geometries
- Geometry models for more complex geometry
- Identification of worst case defects
- Assessment of the above to determine whether, at this stage, it would be beneficial to introduce additional beam angles to reduce misorientation
- A defect response model for embedded worst case defects
- Parametric studies on small blocks for surface-breaking and near-surface worst case defects where the defect response model is not valid
- Parametric studies of relevant additional factors such as cladding
- A survey of relevant previous data

- Application of factors for defect roughness where relevant

What is included in a particular TJ is determined from assessment of each case individually. The process then proceeds according to the outcome of the assessment of defect response in the TJ:

- If the TJ indicates responses above the recording level then the case is made with regard to detection.
- If the TJ indicates insufficient response in some cases, consideration should be given to improving the inspection and repeating the assessment.
- If the case for embedded worst case defects based on modelling or existing experimental data still cannot be made, it may be necessary to use large test pieces containing such defects to avoid any conservatisms in the modelling or existing data. The restriction to use of worst-case defects in the test piece, based on the assessment in the TJ, simplifies the test piece design and construction.
- If the case for surface-breaking and near-surface defects or for embedded defects based on parametric blocks cannot be made the inspection may be intrinsically incapable of achieving all or some of its objectives.

6. Conclusions and Recommendations

6.1 The second pilot study has been largely successful in showing that technical justifications (TJs) have the potential to reduce or remove the need for large scale test pieces in qualification. Resource restrictions prevented parametric studies from being applied as in a real qualification.

6.2 TJs may identify the need for improvements in the inspection if it is to meet its objectives. There is a danger if inspections are carried out before the TJ is produced that they may be inadequate and may have to be repeated.

6.3 Data from studies reported in the literature can provide valuable information very cost-effectively but checks must be made that the essential parameter values make the work relevant.

6.4 TJs should be structured as described in reference 14 and contain the information identified in Section 5.6 of this report.

6.5 Models are available which give largely conservative predictions of defect response when used within their regimes of validity. In the pilot study, models A and C were conservative in nearly every case within their regime of validity.

6.6 All models used in TJs should be experimentally validated.

6.7 The methods used to incorporate defects into the test piece used in the pilot study are capable of producing defects with parameters very close to those specified.

6.8 The analysis of essential parameters carried out in the TJ illustrates the success of the approach contained in Issue 2 of the Recommended Practice on essential parameters (reference 15).

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Appendix 1 – Inspection Results from the Nozzle Test Piece

Appendix 1.1– Inside Inspection Results Summary – Unclad Test Piece

Defect[2]	Defect Details[1]	60º Shear	45º Tandem	70º TRL fd 12mm	70º TRL fd 8mm
1	5, 0, 0, 0		19% FSH (1)	+ve Dir – 37% FSH (0) -ve Dir – 37% FSH (0)	+ve Dir – 36% FSH (0) -ve Dir - 47% FSH (2)
8	5, 0, 10, 5		17% FSH (1)	-ve Dir – 85% FSH (5)	-ve Dir – 65% FSH at 6dB lower sensitivity (4)
9	10, 0, 4, 0		32% FSH (12)	+ve Dir – 57% FSH (2) -ve Dir – 23% FSH (0)	+ve Dir – 71.5% FSH (11) -ve Dir – 37% FSH (0)
10	10, 0, 20, 5			+ve Dir – 55% FSH at 6dB lower sensitivity (5) -ve Dir – 13% FSH (0)	+ve Dir – 62% FSH at 6dB lower sensitivity (6) -ve Dir – 17% FSH (0)
11	15, 0, 10, 0		20% FSH (4)	+ve Dir – 69% FSH (18) -ve Dir – 26% FSH (0)	+ve Dir – 88% FSH (13) -ve Dir – 32% FSH (0)
12	15, 0, 0, 5		37% FSH (6)	+ve Dir – 46% FSH (1) -ve Dir – 35% FSH (0)	+ve Dir – 55% FSH (4) -ve Dir – 48% FSH (3)
13	10, 3, 4, 0		44% FSH (8)	+ve Dir – 72% FSH at 6dB lower sensitivity (6) -ve Dir – 30% FSH (0)	+ve Dir – 82% FSH at 6dB lower sensitivity (7) -ve Dir – 21% FSH (0)
14	15, 12, 4, 0	+ve Dir – 29% FSH (13) -ve Dir – 27% FSH (8)	79% FSH at 3dB lower sensitivity (18)	+ve Dir – 70% FSH (10) -ve Dir – 22% FSH (0)	+ve Dir – 46% FSH (2)
15	15, 22, 4, 0	+ve Dir – 28% FSH (6)	85% FSH at 6dB lower sensitivity (13)	+ve Dir – 54% FSH (8)	
16	5, 2, 4, 0		65% FSH (19)	+ve Dir – 44% FSH (3) -ve Dir – 45% FSH (0)	+ve Dir – 38% FSH (0) -ve Dir – 45% FSH (2)
17	5, 7, 4, 0		84% FSH (22)	+ve Dir – 90% FSH (19) -ve Dir – 41% FSH (0)	+ve Dir – 54% FSH (3) -ve Dir – 49% FSH (2)

Note: 1. Defect details are given as through-wall extent (mm), ligament to inspection surface (mm), tilt (degrees), skew (degrees).

2. Defects 2 to 7 inclusive are surface breaking defects in the clad block and so did not exist when the unclad block was inspected.
3. Positive direction (+ve Dir) is with the probe on the nozzle side of the weld with the beam directed away from the nozzle.
4. Negative direction (-ve Dir) is with the probe on the side of the weld away from the nozzle with the beam directed towards the nozzle.
5. The tandem inspection is always applied in the negative direction because there is insufficient space for both transducers on the nozzle side of the weld.
6. The entries in the table are peak observed reflection amplitudes at the inspection sensitivity. The figure in brackets after the observed peak reflection amplitude is the number of consecutive scan lines on which the defect was observed above the recording level. When the peak signal is significantly below the recording level a zero is given for the number of scan lines.
7. In some cases the peak reflection amplitude exceeded 100% FSH. In these cases the scan was repeated at 3 or 6dB lower sensitivity and the amplitude so obtained is the one recorded in the table. This situation is noted in the table where appropriate.

Appendix 1.2 – Outside Inspection Results Summary – Clad Test Piece

Defect	Defect Details[1]	45º Shear	60º Shear	45º Shear Tandem
1	5, 155, 0, 0	97.5% FSH (12)[2]	31% FSH (6)	46% FSH (7)
2	5, 163, 0, 0	42% FSH (6)	47% FSH (6)	
3	5, 163, 10, 5	28% FSH (5)		
4	10, 158, 10, 0	65% FSH (9)	27% FSH (7)	33% FSH (4)
5	10, 158, 0, 0	35% FSH (8)	28% FSH (10)	
6	15, 153, 0, 5	41% FSH (16)	35% FSH (14)	52% FSH (13)
7	15, 153, 20, 5	54% FSH (24)	80% FSH (14)	36% FSH (11)
8	5, 155, 10, 5			
9	10, 150, 4, 0	64% FSH (14)	31% FSH (12)	53% FSH (7)
10	10, 150, 20, 5		36% FSH (12)	50% FSH (11)
11	15, 145, 10, 0	85% FSH (19)	33% FSH (11)	43% FSH (9)
12	15, 145, 0, 5	53% FSH (19)	35% FSH (14)	73% FSH (18)
13	10, 147, 4, 0	38% FSH (12)	35% FSH (8)	62% FSH (6) at 6dB reduction in sensitivity[3]
14	15, 132, 4, 0	34% FSH (8)	35% FSH (11)	74% FSH (14) at 6dB reduction in sensitivity
15	15, 122, 4, 0	28% FSH (4)	32% FSH (8)	34% FSH (12)
16	5, 152, 4, 0	69% FSH (16) at 6dB reduction in sensitivity	42% FSH (19)	84% FSH (11)
17	5, 147, 4, 0	59% FSH (16) at 6dB reduction in sensitivity	44% FSH (20)	73% FSH (19) at 6dB reduction in sensitivity

Note:
1. Defect details are given as through-wall extent (mm), Ligament to inspection surface (mm), Tilt (degrees), Skew (degrees).
2. The entries in the table are peak observed reflection amplitudes at the inspection sensitivity. The figure in brackets after the observed peak reflection amplitude is the number of scan lines on which the defect was observed above the recording level. When the peak signal is below the recording level a zero is given for the number of scan lines.
3. In some cases the peak reflection amplitude exceeded 100% FSH. In these cases the scan was repeated at 6dB lower sensitivity and the amplitude so obtained is the one recorded in the table. This situation is noted above where appropriate.

Appendix 1.3 – Inside Inspection Results Summary – Clad Test Piece

Probe	Defect 1 (20 x 5 mm)	Defect 2 (20 x 5 mm)	Defect 3 (20 x 5 mm)	Defect 4 (40 x 10 mm)	Defect 5 (40 x 10 mm)	Defect 6 (60 x 15 mm)	Defect 7 (60 x 15 mm)	Defect 8 (20 x 5 mm)	Defect 9 (40 x 10 mm)
70 TRL FD8 NEG	- 9.1 dB	ND	ND	- 8.8 dB	- 6.8 dB	- 12.0 dB	**+ 4.5 dB**	**- 2.4 dB**	- 6.2 dB
70 TRL FD8 POS	- 8.0 dB	ND	ND	**- 0.3 dB**	**- 4.8 dB**	**- 1.6 dB**	ND	- 8.8 dB	**- 0.2 dB**
70 TRL FD12 NEG	- 6.2 dB	ND	ND	- 11.5 dB	**- 2.6 dB**	- 9.9 dB	**+ 4.8 dB**	**+ 1.0 dB**	- 6.4 dB
70 TRL FD12 POS	- 7.5 dB	ND	ND	**+ 1.4 dB**	**- 1.9 dB**	**- 1.3 dB**	- 10.4 dB	- 10.1 dB	**- 4.0 dB**
T60 NEG									
T60 POS									
T70 NEG									
T70 POS									
T45 TANDEM NEG	- 24.1 dB	ND	ND	- 24.8 dB	- 19.1 dB	- 14.7 dB	ND	ND	- 26.3 dB

Probe	Defect 10 (40 x 10 mm)	Defect 11 (60 x 15 mm)	Defect 12 (60 x 15 mm)	Defect 13 (20 x 10 mm)	Defect 14 (30 x 15 mm)	Defect 15 (30 x 15 mm)	Defect 16 (50 x 5 mm)	Defect 17 (60 x 5 mm)
70 TRL FD8 NEG	**- 5.5 dB**	- 7.7 dB	- 10.7 dB	- 7.9 dB	ND	ND	**- 0.9 dB**	- 10.5 dB
70 TRL FD8 POS	**+ 6.1 dB**	**+ 1.9 dB**	**- 2.1 dB**	**- 0.2 dB**	ND	ND	**- 3.5 dB**	- 11.9 dB
70 TRL FD12 NEG	- 7.7 dB	- 6.2 dB	- 15.7 dB	- 8.2 dB	- 10.1 dB	ND	**- 3.2 dB**	- 7.0 dB
70 TRL FD12 POS	**+ 7.9 dB**	**- 0.8 dB**	- 8.1 dB	**+ 3.7 dB**	**- 4.4 dB**	**- 4.6 dB**	**- 4.8 dB**	**- 6.0 dB**
T60 NEG					- 17.2 dB	- 13.6 dB	**- 7.2 dB**	-12.3 dB
T60 POS					**- 11.5 dB**	- 17.0 dB	ND	ND
T70 NEG					ND	**- 6.7 dB**	**- 5.4 dB**	**- 7.5 dB**
T70 POS					**- 9.1 dB**	- 15.0 dB	**- 10.1 dB**	- 14.1 dB
T45 TANDEM NEG	ND	- 23.9 dB	- 17.4 dB	**- 11.2 dB**	**+ 4.1 dB**	**- 5.3 dB**	- 16.9 dB	**- 11.4 dB**

ND: No Detection

Bold Underline: Detection within the procedure criteria (TRL: Ref level ÷ 6 dB, Shear: Ref level ÷ 12 dB)

Other numbers Detection under procedure evaluation criteria

Appendix 2 – Modelling Predictions of Defect Response

Appendix 2.1 – Predictions for Inspection from the Inside – Unclad Test Piece

								Responses (dB relative to DAC)						
Defect	**Type**	**Height**	**Length**	**Ligament to inner unclad surface**	**Tilt**	**Skew**	**Probe angle**	**Expt**	**Model A**	**Model B**	**Model C**	**Model A minus expt**	**Model B minus expt**	**Model C minus expt**
		mm	**mm**	**mm**	**deg**	**deg**	**deg**	**dB**	**dB**	**dB**	**dB**	**dB**	**dB**	**dB**
1	PISC Type A	5	20	0	0	0	45-			-22.0				
							60-			29.2				
							70-			32.3				
							Tandem	-12.5		-0.2			12.3	
9	PISC Type A	10	40	0	-4	0	45-			26.6	-14.0			
							60-			22.0	-12.8			
							70-			24.7	-8.3			
							Tandem	-8		21.0			29.0	
10	PISC Type A	10	40	0	-20	5	45-				-15.1			
							60-				-13.6			
							70-				-12.8			
11	PISC Type A	15	60	0	-10	0	45-				-14.8			
							60-		-7.9		-13.6			
							70-		-3.0		-12.7			
12	PISC Type A	15	60	0	0	5	45-				-14.3			
							60-		-4.3		-13.3			
							70-		-3.3		-8.3			

								Responses (dB relative to DAC)						
Defect	**Type**	**Height**	**Length**	**Ligament to inner unclad surface**	**Tilt**	**Skew**	**Probe angle**	**Expt**	**Model A**	**Model B**	**Model C**	**Model A minus expt**	**Model B minus expt**	**Model C minus expt**
		mm	**mm**	**mm**	**deg**	**deg**	**Deg**	**dB**	**dB**	**dB**	**dB**	**dB**	**dB**	**dB**
13	LOSWF	10	20	3	-4	0	45-			16.1	-20.1			
							60-		-14.1	10.9	-19.0			
							70-		-10.1	13.5	-15.6			
							TRL70(8)-	-11.6			-8.0			3.6
							TRL70(8)+	6.2			9.5			3.3
							TRL70(12)-	-8.5			-10.7			-2.2
							TRL70(12)+	5.1			6.3			1.2
							Tandem	-5.2		14.1	-13.5		19.3	-8.3
14	LOSWF	15	30	13	4	0	45-			8.6	-19.6			
							60-	-9.4	-10.9	8.8	-14.7	-1.5	18.2	-5.3
							60+	-8.8			-12.7			-3.9
							70-	-3.2	-7.8	6.1	-12.1	-4.6	9.3	-8.9
							70+	0.2			-9.7			-9.9
							TRL70(8)+	-4.8			-7.4			-2.6
							TRL70(12)-	-11.2			-6.9			4.3
							TRL70(12)+	-1.2			-4.5			-3.3
							Tandem	2.9	-2.0	14.5	-5.2	-4.9	11.6	-8.1
15	LOSWF	15	30	23	-4	0	45-			-2.5	-19.9			
							60-		-13.2	6.5	-18.6			
							60+	-9.1			-9.1			0
							70-	-5.8	-9.5	7.4	-15.1	-3.7	13.2	-9.3
							70+	3.5			-4.3			-7.8
							TRL(12)+	-3.4			-3.7			-0.3
							tandem	6.5	-1.6	14.0	-5.5	-8.1	7.5	-12.0

								Responses (dB relative to DAC)						
Defect	**Type**	**Height**	**Length**	**Ligament to inner unclad surface**	**Tilt**	**Skew**	**Probe angle**	**Expt**	**Model A**	**Model B**	**Model C**	**Model A minus expt**	**Model B minus expt**	**Model C minus expt**
		mm	**mm**	**mm**	**deg**	**deg**	**deg**	**dB**	**dB**	**dB**	**dB**	**dB**	**dB**	**dB**
16	LOSWF	5	50	3	4	0	45-				-18.9			
							60-				-13.9			
							70-				-8.7			
							TRL70(8)-	-5			2.9			7.9
							TRL70(8)+	-6.5			0.8			7.3
							TRL70(12)-	-5			-0.9			4.1
							TRL70(12)+	-5.2			-2.4			2.8
							tandem	-1.8			-23.4			-21.6
17	LOSWF	5	60	8	-4	0	45-				-19.4			
							60-		-12.2		-17.9			
							70-		-8.7		-13.4			
							TRL70(8)-	-4.3			-1.7			2.6
							TRL70(8)+	-3.4			-1.3			2.1
							TRL70(12) -	-5.8			-5.2			0.6
							TRL70(12)+	1			-0.2			-1.2
							tandem	0.4			-14.6			-15
											Max	-1.5	29.0	7.9
											Min	-8.1	7.5	-21.6
											Mean	-4.6	15.1	-2.9
											Number	5	8	28
											St Dev	2.4	6.9	7.0

Note: 1. Shaded entries above are where there are caveats in the result because the model has been applied beyond its strict regime of validity or because approximations have been made (see reference 14 for more details).

2. Under "Probe angle", + or – indicate the direction of probe scanning.

Appendix 2.2 – Predictions for Inspection from the Outside – Clad Test Piece

								Responses (dB relative to DAC)				Model prediction minus experiment		
Defect	**Type**	**Height**	**Length**	**Ligament to inner unclad surface**	**Tilt**	**Skew**	**Probe angle**	**Expt**	**Model A**	**Model B**	**Model C**	**Model A minus expt**	**Model B minus expt**	**Model C minus expt**
		mm	**mm**	**mm**	**deg**	**deg**	**deg**	**dB**	**dB**	**dB**	**dB**	**dB**	**dB**	**dB**
9	PISC Type A	10	40	0	-4	0	45	-1.9	0.0	6.2	-1.1	1.9	8.1	0.8
							60	-8.3	-28.0	0.9	-4.9	-19.7	9.2	3.4
							Tandem	-5.3		-7.8			-2.5	
10	PISC Type A	10	40	0	-20	5	45		-27.0					
							60	-6.9	-15.0		-12.1	-8.1		-5.2
11	PISC Type A	15	60	0	-10	0	45	0.5	-14.0	-0.4	-7.5	-14.5	-0.9	-8.0
							60	-7.8	-20.0	-7.9	-11.6	-12.2	-0.1	-3.8
							Tandem	-5.4		-21.4			-16.0	
12	PISC Type A	15	60	0	0	5	45	-3.6	-33.0		-24.7	-29.4		-21.1
							60	-7.3	-26.0		-20.4	-18.7		-13.1
13	LOSWF	10	20	3	-4	0	45	-6.4	-6.0	0.3	-9.7	0.4	6.7	-3.3
							60	-7.3	-12.0	-3.4	-11.0	-4.7	3.9	-3.7
							Tandem	5.3		-17.1			-22.4	
14	LOSWF	15	30	13	4	0	45	-7.5	-9.0	17.3	-13.7	-1.5	24.8	-6.2
							60	-7.1	-13.0	6.2	-8.6	-5.9	13.3	-1.5
							Tandem	6.8		-7.7			-14.5	
15	LOSWF	15	30	23	-4	0	45	-9.2	-22.0	0.0	-14.8	-12.8	9.2	-5.6
							60	-7.9	-28.0	-1.4	-8.0	-20.1	6.5	-0.1
							Tandem	-7.5		-14.7			-7.2	

								Responses (dB relative to DAC)				Model prediction minus experiment		
Defect	**Type**	**Height**	**Length**	**Ligament to inner unclad surface**	**Tilt**	**Skew**	**Probe angle**	**Expt**	**Model A**	**Model B**	**Model C**	**Model A minus expt**	**Model B minus expt**	**Model C minus expt**
		mm	**mm**	**mm**	**deg**	**deg**	**deg**	**dB**	**dB**	**dB**	**dB**	**dB**	**dB**	**dB**
16	LOSWF	5	50	3	4	0	45	4.7	-4.0	10.1	-2.8	-8.7	5.4	-7.5
							60	-5.6	-35.0	2.2	-6.0	-29.4	7.8	-0.4
							Tandem	0.4		-17.8			-18.2	
17	LOSWF	5	60	8	-4	0	45	3.3	1.0	8.5	-9.3	-2.3	5.2	-12.6
							60	-5.2	-11.0	0.1	-6.4	-5.8	5.3	-1.2
							Tandem	6.7		-14.6			-21.3	

All results where corner effect has been calculated i.e. 45º results for model A, 45º and 60º results for models B and C, all defects except 10 and 12. (All non-shaded results above)			
Max	**1.9**	**24.8**	**3.4**
Min	**-14.5**	**-0.9**	**-12.6**
Mean	**-5.4**	**7.5**	**-3.6**
Number	**7**	**14**	**14**
St Dev	**6.6**	**6.2**	**4.2**

Note:
1. Shaded entries above are where there are caveats in the result because the model has been applied beyond its strict regime of validity or because approximations have been made (see reference 14 for more details).
2. All scans above are in the negative direction towards the nozzle.
3. The corner effect is not included in the calculations above for defects 10 and 12 nor for any defects with the 60º probe in the case of model A.
4. The corner effect is not included in the calculations above for defects 10 and 12 in the case of model C.

The following points have been made by the organisation applying model A about their own model. Points 1, 3, 4 and 6 apply to all three models:

1. Because of the curved geometry of the component's outer surface (the scanning surface), the effective tilts of the defects, as seen by the ultrasonic probes, are different from their actual tilts in the test piece. This effect has been taken into account in the modelling.

2. It has been assumed that the probes always point radially inwards on the inspection surface, in the radial-axial plane. Because of the nozzle geometry this means that the beam axis is skewed out of the radial-axial plane at all azimuthal positions except 0, 90, 180 and 270°. This means that even unskewed defects are skewed with respect to the probe beam. This skew has been taken into account in the modelling.

3. Although allowance is made for the above effects, the model basically assumes a flat plate geometry, so does not fully model the complex nozzle-to-shell weld geometry.

4. In order to find the probe position giving the peak predicted echo amplitude, the models simulate the scanning of the probe locally in primary and secondary directions around the position where the beam axis points directly at the defect. A flat plate scanning surface is assumed for this local scanning, tangent to the local true outer surface.

5. The PISC Type A defects are modelled as semi-ellipses having the same areas and heights as the true defects, which are segments of circles. (The model cannot handle segments of circles directly.) The LOF defects are assumed to be rectangular. All defects are assumed to be smooth and with sharp tips.

6. The thickness of the cladding has been included when setting the component thickness. Any effects of the cladding on the ultrasonic response have not been modelled.

7. To reduce the workload, only the 45° shear probe responses with corner effect have been modelled, and only for 7 selected defects (9, 11, 13, 14, 15, 16, 17). The model could equally have been applied to the remaining defects and to the 60° probe.

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Final Report of the ENIQ 2nd Pilot Study

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Abstract
The present report gives an overall picture of the ENIQ 2nd Pilot Study, where the potential of technical justifications (TJ) to reduce the number of test piece trials in the qualification of ultrasonic inspection procedures for non-destructive tests was investigated. As the subject of the study a ferritic BWR-type nozzle to shell weld was selected. A TJ, partly relying on mathematical modelling, was produced to predict whether a designated ultrasonic inspection would be successful in detecting the specified defects. In parallel, a test piece with deliberately introduced defects was fabricated and inspected with the inspection system specified in the TJ. Predictions and inspection results were compared. In addition, as a separate exercise, three different mathematical models were used to predict the ultrasonic responses of the defects in the test piece to provide information on model applicability and accuracy of prediction.

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