

Project CPD5 - Report 4
DISSEMINATION, STANDARDISATION AND REVIEWS

**Validation of Procedures for Ultrasonic C-Scan
Inspection of PMCs: International Round-Robin**

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Validation of Procedures for Ultrasonic C-Scan Inspection of PMCs: International Round-Robin

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ABSTRACT

Ultrasonic C-scan is the most widely used inspection technique for quality/process control and in-service monitoring of composite structures. Although considerable capital and operational costs are involved, the reliability and traceability of this method is limited due to the absence of international standards and/or universally accepted procedures.

To meet this need, three procedures were drafted in 1997 as part of a research programme that investigated several fundamental aspects of the technique. The procedures covered operation of C-scan equipment, calibration of ultrasonic transducers and production of reference panels with simulated defects. The programme, "Standardised Procedures for Ultrasonic Inspection of Polymer Matrix Composites", was funded under the CARAD scheme of the DTI.

This report presents the results of the International phase of a round-robin (R-R) validation exercise of the operational procedure undertaken by several users. The report includes recommendations by the international participants for improvements to the standardised procedures. Concurrently, the procedures have been re-formatted by BSI and submitted to technical committee BSI ACE/56 (NDT) for consideration as a new work item for AECMA standardisation.

The main results of the international R-R exercise were: (i) defect size was similar to those participants in the UK R-R exercise that sized the defects using the -6 dB defect method; independent of the size, shape and through-thickness location of the insert; (ii) absolute attenuation measurements (not currently practiced) was also in good agreement with the UK participants; and (iii) the procedures have encouraged operators to adopt a methodical approach to C-scan set-up, inspection and documentation, highlighting all the relevant controlling parameters. These R-R results will be used to support the draft standards and to provide precision statements in the finalised standards. This report also provides brief overviews of the objectives and activities of the prior programme.

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Approved on behalf of Managing Director, NPL, by Dr C Lea,
Head of NPL Materials Centre.

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1 INTRODUCTION

The increasing use of composite materials in critical structural components, combined with stringent requirements for safety and quality assurance, has resulted in considerable investment in the development of non-destructive evaluation (NDE) methods suited to the characterisation of these heterogeneous materials. A number of techniques have been developed of which ultrasonic C-scan inspection is the most widely used. This technique is used to detect, measure and characterise a wide range of manufacturing and in-service defects in composite materials and is routinely used in the aerospace industry, often using large and expensive facilities with commensurate operating costs.

A review in 1993 [1] found that there were no standards or universally accepted procedures for the ultrasonic C-scan inspection of composites, and as a result of this absence, the reliability and traceability of the method was limited. Available standards are directed towards the inspection of metals. Companies within the aerospace industry undertook their inspections according to different procedures set down by major aerospace companies or to routines developed in-house.

A research programme was undertaken in 1994-1997 to establish a firm basis for a new set of procedures, which would be offered as the basis of future standards. Several benefits were expected from the availability of standard procedures, including:

- *Improved safety and quality assurance*
- *Reduced production and maintenance costs*
- *Reduced risk of human error*
- *Optimisation of manufacturing and processing methods*
- *Improved confidence in long-term performance*

This programme was funded under the Commercial Aircraft Research and Development (CARAD) programme funded by the United Kingdom Department of Trade and Industry (DTI) and resulted in both extensive scientific data and three draft procedures covering:

- *Operational procedure for ultrasonic C-scan equipment*
- *Ultrasonic transducer calibration procedure*
- *Procedure for the preparation of reference panels with simulated defects*

These drafts have been submitted to the technical committee BSI ACE 56 (NDT) for consideration as a new work item for AECMA standardisation. The longer-term objective is for ISO (International Standards Organisation) standardisation. At the same time, support was obtained from the Engineering Industries Directorate (DTI) to conduct national and international round-robin (R-R) validation exercises to generate precision data and to identify any necessary adjustments to the procedures. The results from the international R-R participants are given in this report together with a brief overview of the research objectives and activities of the prior CARAD programme (see also NPL Report CMMT(A) 179 [2]). The report includes recommendations by the international participants for improvements to the standardised procedures. Recommendations have been received from non-participants of the R-R exercise and from co-authors of the procedures. It is intended that these recommendations be addressed as part of the AECMA working group review (to be confirmed). The UK round-robin results were presented in NPL Report CMMT(A) 179 [2].

2 SUMMARY OF PRIOR "CARAD" RESEARCH PROGRAMME

In response to the need identified in the industrial survey, a research programme "Standardised Procedures for Ultrasonic Inspection of Polymer Matrix Composites" was formulated at NPL in the Centre for Materials Measurement and Technology. Funding was obtained from DTI under the CARAD initiative.

The research was undertaken between March 1994 and February 1997 in the NPL Materials Centre with support from the Centre for Mechanical and Acoustical Metrology (CMAM) at NPL and the Structural Materials Centre at the Defence Evaluation and Research Agency (DERA), Farnborough. An Industrial Advisory Group (IAG), consisting of ultrasonic test equipment manufacturers/suppliers and end-users, participated in the work. Their advice and involvement ensured the industrial relevance and future applicability of the work.

The programme was designed to identify the technical requirements, which needed to be established in support of the standardised procedures. The main aim of the programme was to enable C-scan techniques to be placed on a sound and traceable basis. Individual objectives were:

- *To develop basic "operational" procedures, possibly through harmonisation of existing methods*
- *To develop calibration procedures for ultrasonic transducers*
- *To assess the effects of the "acoustic properties" of the overall system on quantitative measurements and make recommendations on system tolerances*
- *To establish standard reference panels with simulated representative production type defects*
- *To consider methods for porosity measurement*

3 ULTRASONIC C-SCAN PROCEDURES - WORKING DRAFTS

Three working draft procedures for the ultrasonic C-scan inspection of composite structures were produced in the prior CARAD research programme. The results of this supporting research programme are summarised in a collection of papers in the January 1998 edition of the Journal INSIGHT "Non-destructive Testing and Condition Monitoring" [3-7].

The draft documents have mainly adopted the definitions and terms in the draft European Standard on Non-Destructive Testing - Terminology - Part 4: Terms used in Ultrasonic Testing (prEN 1330-4). Additional and alternative terminologies to those used in prEN 1330-4 have been used as necessary.

3.1 PART 1 - OPERATIONAL PROCEDURE

This draft specifies three methods for ultrasonic C-scan inspection:

Method 1 - Pulse echo (both immersion and contact)

Method 2 - Single through-transmission (both immersion and water-jet)

Method 3 - Double through-transmission

The methods specified in this draft are applicable to transducers operating in the frequency range 0.5 to 20 MHz.

For each of these three methods of operation, three different measurements are considered:

- *Relative attenuation measurement by comparison with a reference standard scanned alongside the test component. This type of measurement may be used for defect detection and characterisation.*
- *Absolute attenuation measurement, which could lead to the determination of bulk attenuation - a property of the specimen.*
- *Defect sizing of planar defects in laminates.*

Three different methods of coupling the ultrasound into the composite are covered: water tank immersion systems, water-jet systems, and contact inspection. The procedure can be used with non-aqueous immersion systems provided there are no special exceptions. The methods are considered suitable for use with carbon and glass fibre-reinforced thermoset and thermoplastic matrix composites incorporating unidirectional or non-unidirectional reinforcements in both a continuous or discontinuous format, and woven fabrics.

3.2 PART 2 - TRANSDUCER CALIBRATION PROCEDURE

This document specifies test methods for determining the beam properties of immersion ultrasonic transducers according to the specifications in Part 1 of this draft. The document specifies test methods for both focused and unfocused circular ultrasonic transducers operating in the frequency range 0.5 - 20 MHz, using both pulse-echo and hydrophone based techniques. The document incorporates technology not present in other international or national standard calibration procedures.

3.3 PART 3 - PREPARATION OF REFERENCE DEFECTS AND DEFECT PANELS

This procedure, based on ISO/DIS 1268 [10], describes the preparation of reference panels fabricated from fibre-reinforced plastic composites with simulated production defects. The panels may be used to adjust the sensitivity and/or resolution of ultrasonic C-scan equipment and to aid with the detection of defects. The procedure can be used with laminates with continuous unidirectional reinforcement and woven fabrics with thermosetting resins.

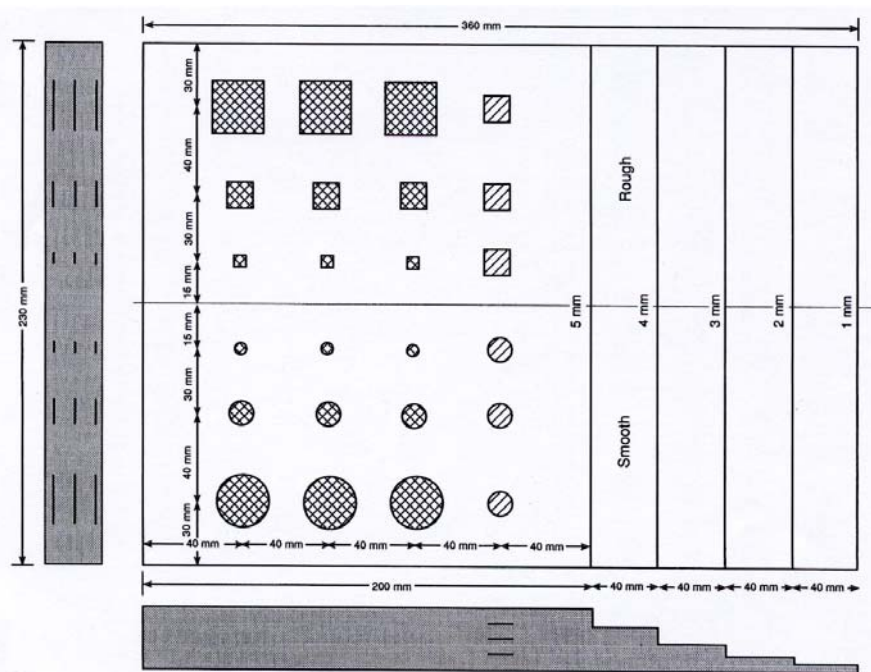


Figure 1: Stepped laminate panel with circular and square inserts.

4 REFERENCE PANEL AND PERSPEX™ DEFECT BLOCK

A stepped reference panel (Figure 1) manufactured from carbon fibre-reinforced epoxy was circulated to a number of establishments within the USA. Each participant was required to inspect the reference panel using the operational procedures in Part 1 (See Section 3.1). Participants were requested to carry out absolute attenuation measurements on the stepped reference panel and to size the defects according to the -6 dB defect sizing method [7-8], where possible. A checklist to assist in the evaluation accompanied the draft procedure.

The reference panel (Figure 1), designed and produced at NPL, contained circular and square defects of three different sizes located near the upper and lower surfaces of the laminate and at the mid-plane. The panel, which was 360 mm long and 230 mm wide, contained five discrete steps each 1 mm (i.e. 16 plies) in depth for attenuation measurements. A quasi-isotropic laminate configuration was used. The lay-up per step was $[45^\circ/0^\circ/-45^\circ/90^\circ/90^\circ/-45^\circ/0^\circ/45^\circ]_s$. The panel had a smooth back surface with the front surface partitioned equally into smooth and rough finishes in order to assess the effect, if any, of surface finish on attenuation measurements.

Artificial defects (representing delaminations) 6.35, 12.7 and 25.0 mm in size were fabricated using two layers of 50 μm thick poly-tetrafluoroethylene (PTFE), sealed around the edges with heat-resistant tape to ensure an air gap. The artificial defects were placed between the 2nd and 3rd plies (top row in Figure 1), at the mid-plane (second row from top in Figure 1) and between the 38th and 39th plies (third row from top in Figure 1) in the 5 mm thick section of the panel. The aim was to check the resolution of inspection systems as a function of through-thickness location. The combined effect of the high attenuation defect material and the entrapped air produced a well-defined acoustic barrier, with the air gap preventing almost the entire ultrasonic signal from being transmitted through the artificial defect. Square and circular shaped defects were included to determine the effect, if any, of defect geometry on detection/measurement accuracy. The frequent accidental inclusion of single ply release film in laminates warranted the presence of single layers of square and circular shaped PTFE film positioned within the reference material at three different depths. The

inserts, 12.7 mm in size, were located as shown in Figure 1 (right hand column). One half of the stepped panel was given a smooth finish; the other was given a rough surface finish by leaving the bleed cloth in place during the curing cycle. A typical C-scan image of the reference panel is presented in Figure 2.

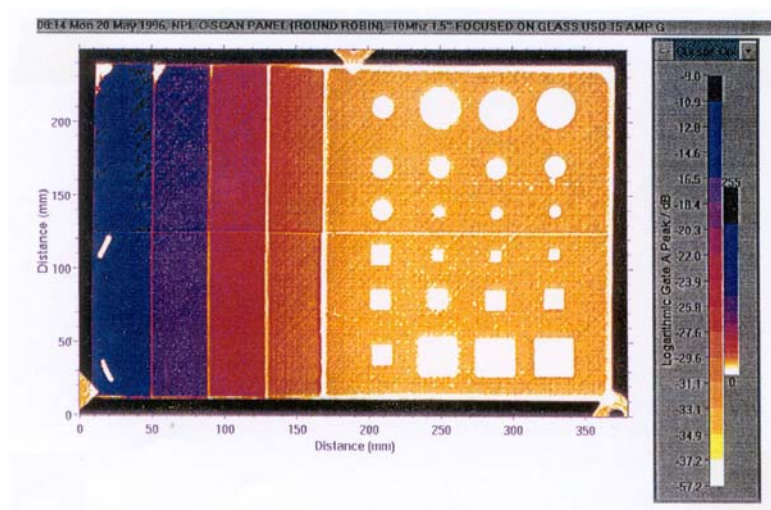


Figure 2: C-scan image of stepped reference panel with defects (courtesy of DERA).

Participants were also requested to inspect a Perspex™ test block (Figure 3) incorporating raised cylinders covering a range of diameters and to size the defects according to the -6 dB defect sizing method. The ends of these cylinders were machined flat to the same height. These cylinders behave as disc reflectors of known diameter. This block was developed by DERA to enable the user to check defect sizing errors for defect gated scans.

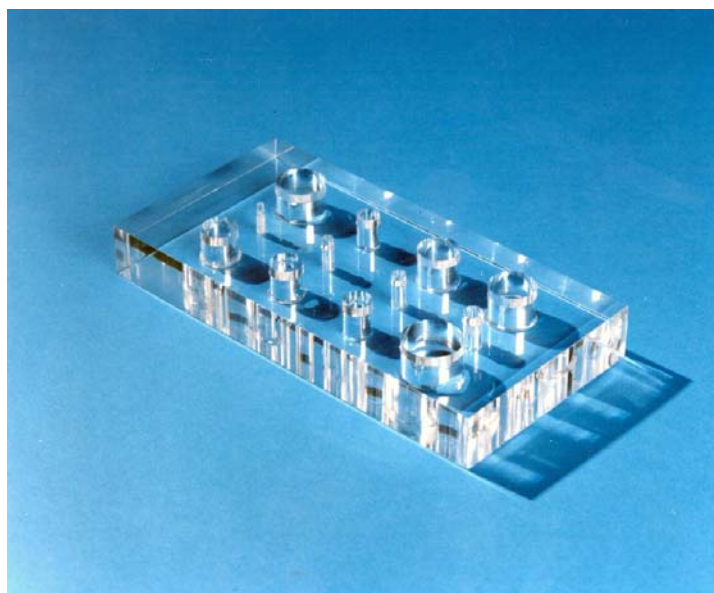


Figure 3: Perspex™ test block with raised cylinders of known diameter.

5 INTERNATIONAL ROUND-ROBIN EXERCISE

Three establishments inspected the reference panel and Perspex™ test block. Methods of inspection included:

- Pulse-echo (immersion and contact)
- Single through-transmission (immersion and water jet)
- Double through-transmission

All participants used more than one method of inspection with two participants using more than one scanning system. This section describes the methods used by each participant to inspect the reference panel and test block and presents a summary of the R-R results. Inspection details and typical C-scan images obtained for the stepped reference panel are presented in Appendix 1.

5.1 INSPECTION DETAILS

5.1.1 Participant A

Participant A inspected the panel using both pulse-echo immersion (back wall echo-gated) and single through-transmission (echo-gated) methods. The pulse-echo test was performed on the reference panel with the steps facing down in the immersion (i.e. water) tank. A goniometer was used to align the transducer perpendicular to the panel surface. The single through-transmission test was performed on the reference panel with steps facing up in the immersion tank. The transmission and receiver transducers were aligned 4 inches (100 mm) apart.

Both pulse-echo immersion and single through-transmission methods were also used to inspect the test block. The test block was inspected with the raised reflectors face down and then face up in an immersion tank. The defect size measurements for each raised reflector on the test block are presented in Section 5.2.

The reference panel and test block were scanned using an Automation Industries US 640 series scanning bridge with a Panametrics pulser (i.e. transmitter)/receiver unit (model 5072PR). Infomerics TestPro software (version 4.1) was used for analysing and displaying the C-scan data. 10 MHz focused PTF transducers with a 2-inch (50 mm) focal length and 0.5 inch (12.5 mm) diameter were used for interrogating the test specimens. Inspection details and C-scan results for the pulse-echo and single through-transmission tests on the reference panel are presented in A1 and A2 of Appendix 1. C-scan inspection details for the test block were similar to those employed for the reference panel.

5.1.2 Participant B

The panel was inspected using pulse-echo (immersion and contact) and double through-transmission methods. The scanning systems and methods of operation employed by Participant B to inspect the reference panel are shown below:

- Boeing Mobile automated scanner (MAUS IV) - pulse-echo (immersion)
- NDT Systems Portascan 007 – pulse-echo (contact)
- Sonix FlexScan – pulse-echo (immersion) and double through-transmission

The MAUS IV scanner was used to produce amplitude (back-wall echo-gated) and time-of-flight (thickness-gated) images of the reference panel. Tests were conducted using 5 MHz and 10 MHz transducers. Amplitude and time-of-flight C-scan images of the reference panel are shown in A3 of Appendix 1. The Portascan 007 results for the reference panel, shown in A4 of Appendix 1, were obtained using a 12 MHz transducer (no additional details supplied).

Pulse-echo immersion and double through-transmission scans were carried out on the reference panel using the Sonix FlexScan C-scan system. This system was also used in pulse-echo (immersion) mode to inspect the test block. A 5 MHz focused transducer with a 2.5-inch (63.5 mm) focal length and 0.5 inch (12.5 mm) diameter was used for interrogating the reference panel and test block. C-scan results obtained using the Sonix FlexScan are shown in A5 of Appendix 1.

5.1.3 Participant C

Participant C inspected the reference panel using single through-transmission in immersion and water-jet modes. Test details and C-scan images are presented in A6 and A7 of Appendix 1. A Cal Data scanner system with a Krautkramer USIP-20 pulser/receiver unit was used for the immersion test. The water-jet scanner (including pulser/receiver system, data acquisition and display software) was designed and developed by Boeing. 5 MHz transducers were used for immersion test and 1 MHz transducers for the water-jet scan. The 1 MHz transmission transducer used for water-jet scanning was driven by a 5 MHz tone burst producing a high amplitude narrow band signal output. The 5 MHz harmonic was used for signal analysis. Three attenuation levels (i.e. -6 dB, -5 dB and -3.3 dB) were used for sizing the defects in the reference panel. The recommended method in the draft procedure is the -6 dB method. The defect size measurements for all three attenuation levels are presented in Section 5.2.

5.2 TEST RESULTS

The three participants were able to detect all 24 defects in the stepped reference panel; independent of the C-scan system, inspection method or inspection parameters (e.g. transducer frequency) used to inspect the reference panel. In most cases, the defects were clearly visible on the C-scan images (see Appendix 1). As previously observed with the UK round-robin results [2], the majority of participants were unable to size the defects using the -6 dB method or measure absolute attenuation due to software or hardware limitations.

Absolute attenuation measurements, which were carried out by one of the participants (Participant B), ranged from 1.0 to 1.4 dBmm⁻¹. These measurements are in good agreement with the UK results, which ranged from 1.2 to 2.0 dBmm⁻¹. It is worth noting that attenuation coefficients tend to increase with increasing frequency of the inspection transducer and depend on the method of inspection.

5.2.1 Reference Panel Results

Only one participant (Participant C) measured the defects in the reference panel. Defect measurements were carried out on both the immersion and water-jet single-through transmission data (see Section 5.1.3). For the immersion data, three attenuation levels (i.e. -6 dB, -5 dB and -3.3 dB) were used for sizing the defects. The defect size measurements in the X- and Y-directions for all three attenuation levels are presented in Tables 1 to 4. In the case of the water-jet test, a single attenuation level (-6.2 dB) was used for defect sizing. The results are presented in Tables 5 and 6. It should be noted that the imperial measurements (i.e. inches) supplied by the participant have been converted to metric (i.e. mm).

**Table 1: R-R Results - Upper-Plane Double-Layered Defect Dimensions (mm)
(Single Through-Transmission - Immersion)**

Insert	-6 dB Sizing	-5 dB Sizing	-3.3 dB Sizing
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Width/Diameter	X-direction	Y-direction	X-direction	Y-direction	X-direction	Y-direction
Square Insert						
25.0 mm	25.4	25.4	25.4	25.4	27.9	25.4
12.7 mm	7.6	7.6	12.7	10.2	15.2	15.2
6.35 mm	0.0	0.0	2.5	2.5	5.1	5.1
Circular Insert						
25.0 mm	22.9	20.3	25.4	25.4	27.9	25.4
12.7 mm	10.2	10.2	12.7	12.7	12.7	12.7
6.35 mm	2.5	2.5	0.0	0.0	7.6	5.1

Table 2: R-R Results - Mid-Plane Double-Layered Defect Dimensions (mm)
(Single Through-Transmission - Immersion)

Insert Width/Diameter	-6 dB Sizing		-5 dB Sizing		-3.3 dB Sizing	
	X-direction	Y-direction	X-direction	Y-direction	X-direction	Y-direction
Square Insert						
25.0 mm	25.4	25.4	25.4	25.4	27.9	25.4
12.7 mm	10.2	12.7	15.2	12.7	15.2	12.7
6.35 mm	0.0	0.0	5.1	2.5	7.6	7.6
Circular Insert						
25.0 mm	25.4	22.9	25.4	22.9	25.4	25.4
12.7 mm	12.7	10.2	12.7	10.2	12.7	12.7
6.35 mm	2.5	2.5	5.1	5.1	7.6	5.1

Table 3: R-R Results - Lower-Plane Double-Layered Defect Dimensions (mm)
(Single Through-Transmission - Immersion)

Insert Width/Diameter	-6 dB Sizing		-5 dB Sizing		-3.3 dB Sizing	
	X-direction	Y-direction	X-direction	Y-direction	X-direction	Y-direction
Square Insert						
25.0 mm	25.4	22.9	25.4	25.4	27.9	27.9
12.7 mm	10.2	10.2	12.7	12.7	12.7	12.7
6.35 mm	2.5	2.5	2.5	2.5	7.6	5.1
Circular Insert						
25.0 mm	22.9	22.9	25.4	25.4	25.4	25.4
12.7 mm	7.9	12.7	10.2	12.7	15.2	12.7
6.35 mm	2.5	2.5	2.5	2.5	5.1	5.1

Table 4: R-R Results - Single-Layered Defect Dimensions (mm)
(Single Through-Transmission - Immersion)

Insert Width/Diameter	-6 dB Sizing		-5 dB Sizing		-3.3 dB Sizing	
	X-direction	Y-direction	X-direction	Y-direction	X-direction	Y-direction
Square Insert						
Upper-Plane	10.2	10.2	10.2	10.2	15.2	15.2
Mid-Plane	12.7	10.2	12.7	12.7	12.7	15.2
Lower-Plane	10.2	10.2	12.7	12.7	15.2	15.2
Circular Insert						
Upper-Plane	10.2	10.2	12.7	12.7	12.7	12.7
Mid-Plane	12.7	12.7	12.7	12.7	15.2	12.7
Lower-Plane	10.2	12.7	12.7	12.7	12.7	12.7

Table 5: R-R Results - Double-Layered Defect Dimensions (mm)
Single Through-Transmission - Water-Jet

Insert Position/Type	X-direction	Y-direction
<u>Upper-Plane/Square Insert</u>		
25.0 mm	26.4	26.4
12.7 mm	10.2	10.2
6.35 mm	6.1	2.0
<u>Upper-Plane/Circular Insert</u>		
25.0 mm	24.4	24.4
12.7 mm	12.2	10.2
6.35 mm	4.1	4.1
<u>Mid-Plane/Square Insert</u>		
25.0 mm	26.4	24.4
12.7 mm	10.2	10.2
6.35 mm	6.1	2.0
<u>Mid-Plane/Circular Insert</u>		
25.0 mm	26.4	24.4
12.7 mm	12.2	10.2
6.35 mm	4.1	4.1
<u>Lower-Plane/Square Insert</u>		
25.0 mm	26.4	24.4
12.7 mm	12.2	12.2
6.35 mm	6.1	6.1
<u>Lower-Plane/Circular Insert</u>		
25.0 mm	22.4	22.4
12.7 mm	12.2	12.2
6.35 mm	2.0	2.0

**Table 6: R-R Results - Single-Layered Defect Dimensions (mm)
Single Through-Transmission - Water-Jet**

Insert Type/Position	X-direction	Y-direction
<u>Square Insert</u>		
Upper-Plane	14.2	12.2
Mid-Plane	12.2	12.2
Lower-Plane	12.2	12.2
<u>Circular Insert</u>		
Upper-Plane	12.2	12.2
Mid-Plane	14.2	14.2
Lower-Plane	12.2	10.2

The following observations were made from the reference panel results:

- All participants detected the single- and double-layered PTFE inserts with the position of the defects being almost identical.
- Differences in apparent defect size were dependent on the inspection technique and inspection parameters. It was not possible to reliably quantify those differences from visual inspection of the C-scan images.
- Uncertainty in defect size increased with decreasing defect size. The 5 dB and 6 dB tend to undersize the defects and the 3.3 dB tends slightly to over-size the defects (i.e. conservative value).
- The apparent defect size increased as the threshold level decreased.
- Absolute attenuation measurements varied from 1.0 to 1.4 dBmm⁻¹ depending on the inspection technique.
- Differences in top surface finish have minimal effect on the relative attenuation measurements.

NB. Although surface roughness can contribute significantly to relative attenuation measurements, in this case, the difference in surface roughness of the two halves on the top surface of the laminate was insufficient to produce a noticeable difference.

5.2.2 Test Block Measurements

Measurements obtained for the raised reflectors of the Perspex™ test block are shown in Table 7. A typical C-scan image of the test block is shown in Figure 4. Only one participant attempted to size the disc reflectors, although two participants scanned the test block. The results showed, as with the stepped reference panel, that uncertainty in defect size tends to increase with decreasing defect size.

**Table 7: R-R Results - Perspex™ Test Block Disc Reflector Diameter (mm)
Pulse-Echo - Immersion**

True Defect Size	Measured Defect Size	% Error
2.98	4	34.2
4.96	6	21.0
6.09	8	31.4
7.99	10	25.2
9.99	12	16.8
12.08	13	7.6
14.04	16	14.0
16.08	18	11.9
17.99	20	11.2
19.90	22	10.6
21.98	23	4.6
25.10	27	7.6

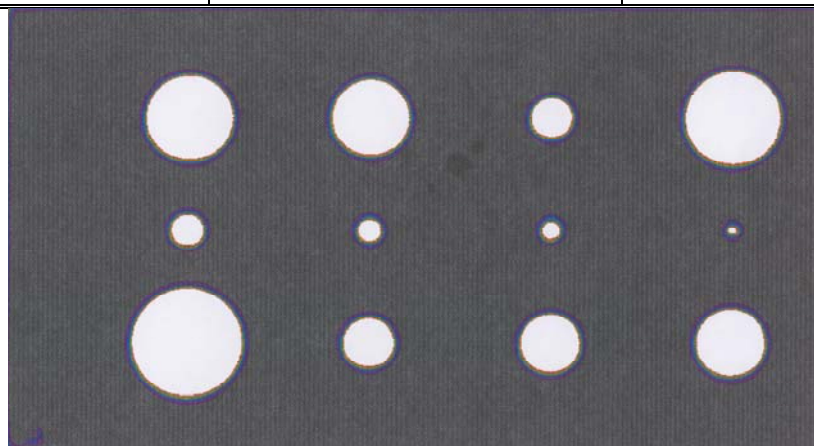


Figure 4: C-scan image of Perspex™ test block with raised cylinders of known diameter.

5.2.3 Comments and Recommendations from Participants

The participants have supplied a number of additional editorial and technical comments (see below). It is intended that recommendations supplied by participants in both the national (see [2]) and international R-R exercises, and by non-participants and co-authors will be addressed as part of AECMA working group review (See Section 1).

- (a) **Concern:** Operational procedure considers the frequency characteristics of the ultrasonic transducer on its own, rather than the transducer/pulser or even the complete C-scan system. Each system has a characteristic frequency response. The response to ultrasonic signals by discontinuities (e.g. porosity and foreign materials) is highly frequency dependent.

Recommendation: The standard to provide guidance to account for variability in frequency dependence of defects (e.g. delaminations and porosity). Alternatively, tighter controls on the characteristic frequency to be used for inspecting different materials and types of defects.

- (b) **Recommendation:** Single broad gate to be used in conjunction with pulse-echo immersion and contact methods to inspect a composite structure with variable thickness (e.g. tapered section).
- (c) **Recommendation:** Instructions to be more clearly and rigorously defined.

6 DISCUSSION AND CONCLUDING REMARKS

The procedures have encouraged operators to adopt a methodical approach to C-scan set-up, inspection and documentation, highlighting all the relevant controlling parameters. The uncertainties associated with defect sizing have been reduced as a result of the introduction of the -6 dB defect sizing method, although further effort is required to encourage the wider use of this technique. Further work is required on the -6 dB method to determine the frequency dependence of diffraction at the defect edge and shadowing by the defect. Also, it is necessary to assess the systematic uncertainties associated with the different inspection modes, particularly double-through transmission, and the frequency dependent response of different defect types (e.g. delaminations and porosity).

A number of methods (e.g. absolute attenuation and defect sizing) within the operational draft procedure will probably need to be simplified with clearly defined mandatory instructions in order to encourage the uptake of the procedures and to maximise the benefits to industry. One end-user, however, indicated that the procedures should be more normative (concise instructions as to inspection parameter values to be used), rather than prescriptive. As previously mentioned, it is intended that recommendations supplied by participants in both the national (see [2]) and international R-R exercises, and by non-participants and co-authors will be addressed as part of the AECMA working group review (to be confirmed).

Future work concerns the wider adoption of the C-scan procedures by industry through their development as national or international standards. These drafts have been submitted to the technical committee BSI ACE 56 (NDT) for consideration as a new work item for AECMA standardisation. The procedures developed within the programme relate only to flat, monolithic panels made from pre-impregnated sheet fabricated using autoclaves. For the procedures to be widely applicable to realistic structures it will be necessary to accommodate other forms of processing and construction. It is intended to broaden the scope of the procedures to include curved structures, sandwich constructions (foam and honeycomb core) and other processing routes (e.g. resin transfer moulding). Part 3 of the procedure would need to be expanded to cover a wider range of defect types associated with other production routes.

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APPENDIX 1

C-Scan Results

A.1 Inspection Details and C-Scan Results - Participant A

Transducer Parameters and System Settings	
Scanning system	Automation Industries, US 640 Series
Pulser/receiver system	Panametrics Model 5072PR
Operation mode	Pulse-echo immersion
Transducer manufacturer	Panametrics
Transducer type	Focused (V311)
Transducer size (mm)	12.5 (0.5")
Transducer frequency (MHz)	10
Transducer focal length (mm)	50 (2")
Focal spot size (mm)	Not specified
Collimator material	Not applicable
Collimator internal diameter (mm)	Not applicable
Water path (mm)	101 (68 μ s)
Scan index (mm)	1.27 (0.05")
Step size (mm)	1.27 (0.05")
Speed (mm/sec)	150 (6"/sec)
Reflector	Not specified
Temperature ($^{\circ}$ C)	21.0 $\pm$ 1.0

A.2 Inspection Details and C-Scan Results - Participant A

Transducer Parameters and System Settings	
Scanning system	Automation Industries, US 640 Series
Pulser/receiver system	Panametrics Model 5072PR
Operation mode	Single through-transmission
Transducer manufacturer	Panametrics
Transducer type	Focused (V311 and V311R)
Transducer size (mm)	12.5 (0.5")
Transducer frequency (MHz)	10
Transducer focal length (mm)	50 (2")
Focal spot size (mm)	Not specified
Collimator material	Not applicable
Collimator internal diameter (mm)	Not applicable
Transducer separation (mm)	100 (4")
Scan index (mm)	0.51 (0.02")
Step size (mm)	0.64 (0.025")
Speed (mm/sec)	100 (4"/sec)
Reflector	Not applicable
Temperature (°C)	21.0 ± 1.0

A.3 Inspection Details and C-Scan Results - Participant B

Transducer Parameters and System Settings	
Scanning system	Boeing Mobile Automated Scanner MAUS IV
Pulser/receiver system	Not specified
Operation mode	Pulse-echo immersion
Transducer manufacturer	Not specified
Transducer type	Not specified
Transducer size (mm)	Not specified
Transducer frequency (MHz)	5 and 10
Transducer focal length (mm)	Not specified
Focal spot size (mm)	Not specified
Collimator material	Not specified
Collimator internal diameter (mm)	Not specified
Stand-off distance (mm)	Not specified
Scan index (mm)	Not specified
Step size (mm)	Not specified
Speed (mm/sec)	Not specified
Reflector	Not specified
Temperature (°C)	Not specified

A.4 Inspection Details and C-Scan Results - Participant B

Transducer Parameters and System Settings	
Scanning system	NDT Systems Portascan 007
Pulser/receiver system	Not specified
Operation mode	Pulse-echo (contact)
Transducer manufacturer	Not specified
Transducer type	Unfocused
Transducer size (mm)	Not specified
Transducer frequency (MHz)	12
Transducer focal length (mm)	Not applicable
Focal spot size (mm)	Not specified
Collimator material	Not applicable
Collimator internal diameter (mm)	Not applicable
Stand-off distance (mm)	Not applicable
Scan index (mm)	Not specified
Step size (mm)	Not specified
Speed (mm/sec)	Not specified
Reflector	Not applicable
Temperature (°C)	Not specified

A.5 Inspection Details and C-Scan Results - Participant B

Transducer Parameters and System Settings	
Scanning system	Sonix FlexScan
Pulser/receiver system	Not specified
Operation mode	Double-through transmission
Transducer manufacturer	Harisonic L6120
Transducer type	Focused
Transducer size (mm)	12.5 (0.5")
Transducer frequency (MHz)	5
Transducer focal length (mm)	63.5 (2.5")
Focal spot size (mm)	Not specified
Collimator material	Not applicable
Collimator internal diameter (mm)	Not applicable
Stand-off distance (mm)	Not specified
Scan index (mm)	1.27 (0.05")
Step size (mm)	1.27 (0.05")
Speed (mm/sec)	150 (6"/sec)
Reflector	Not specified
Temperature (°C)	22-23 (72-73 °F)

A.6 Inspection Details and C-Scan Results - Participant C

Transducer Parameters and System Settings	
Scanning system	Cal Data System
Pulser/receiver system	Krautkramer USIP-20
Operation mode	Single-through transmission (immersion)
Transducer manufacturer	KB Aerotech
Transducer type	Unfocused
Transducer size (mm)	6.35 (0.25")
Transducer frequency (MHz)	5
Transducer focal length (mm)	Not applicable
Focal spot size (mm)	Not applicable
Collimator material	Not applicable
Collimator internal diameter (mm)	Not applicable
Stand-off distance transmitter (mm)	177.8 to 190.5 (7.0 to 7.5")
Stand-off distance receiver (mm)	12.7 to 25.4 (0.5 to 1.0")
Scan index (mm)	2.54 (0.1")
Step size (mm)	2.54 (0.1")
Speed (mm/sec)	Not specified
Reflector	Not specified
Temperature (°C)	Not specified

A.7 Inspection Details and C-Scan Results - Participant C

Transducer Parameters and System Settings	
Scanning system	Boeing System
Pulser/receiver system	Boeing modified Ritec tone burster pulser/Boeing log preamp
Operation mode	Single-through transmission (water jet)
Transducer manufacturer	Not specified
Transducer type	Unfocused
Transducer size (mm)	19.05 (0.75")
Transducer frequency (MHz)	1 (5 MHz harmonic of transducer used)
Transducer focal length (mm)	Not applicable
Focal spot size (mm)	Not applicable
Collimator material	Not specified
Collimator internal diameter (mm)	Not applicable
Stand-off distance transmitter (mm)	38.10 (1.5")
Stand-off distance receiver (mm)	31.75 (1.25")
Scan index (mm)	Not specified
Step size (mm)	Not specified
Speed (mm/sec)	Not specified
Reflector	Not applicable
Temperature (°C)	Not specified