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DISSEMINATION, STANDARDISATION AND REVIEWS

Validation of Procedures for Ultrasonic C-scan Inspection of PMCs : UK Round-Robin

W R Broughton, M J Lodeiro and G D Sims

July 1999

Centre for Materials Measurement and Technology
National Physical Laboratory
NPL Report CMMT(A) 179

NPL

DTI Criteria For Measurement Programmes

a. There must be a significant level of innovation

b. The work must be of high quality

c. The work should contribute to Standards and/or Codes of Practice

d. There should be a width of beneficiaries/users of the work (including by sector and company size)

e. The work should be pertinent to trade

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CPD3: Interface Characterisation and Behaviour

CPD4: Manufacture, Safety and Design: Specific Issues

CPD5: Dissemination, Standardisation and Reviews

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Validation of Procedures for Ultrasonic C-scan Inspection of PMCs : UK 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 gives the results of the UK phase of a round-robin (RR) validation of these procedures undertaken by several equipment manufacturers and users. Concurrently, the procedures have been re-formatted by BSI and submitted by BSI ACE/56 (NDT) as CEN Aerospace standards proposals.

The main results of the RR were: (i) defect size was similar for all participants 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) were in good agreement; 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 RR 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 Centre for Materials Measurement and Technology.

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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 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 CARAD programme funded by DTI (see below) 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 were submitted to BSI for consideration as new work items (NWI) for the CEN (Comité Européen de Normalisation) Aerospace series of standards. 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.

The results from the UK round-robin are given in this report together with a brief overview of the research objectives and activities of the prior CARAD programme. Meanwhile, excellent progress has been made on the formal submission of the original drafts, which have been re-formatted to CEN rules and submitted as proposals for EN Aerospace standards.

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 UK Department of Trade and Industry (DTI) under the Commercial Aircraft Research and Development (CARAD) initiative.

The research was undertaken between March 1994 and February 1997 in CMMT 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*

2.1 REVIEW OF INDUSTRIAL PRACTICES AND REQUIREMENTS

A review was carried out to identify current industrial practices and requirements. The assessment covered procedures/standards for the operation and calibration of C-scan equipment, and methods used for producing reference (calibration) panels incorporating representative production defects. Procedures applicable to quality/process control, manufacturing acceptance and in-service damage assessment were collected from the IAG members and other sources. The result of the assessment was used to guide the experimental programme and to provide the basis for the draft procedures.

The areas covered in the assessment were:

Operational Procedures: Included the ultrasonic set-up used, system parameters, transducer type, collimators, couplants and wetting agents and ultrasonic signal attenuation.

Calibration Procedures: Considered frequency spectrum analysis, beam profiling, focal distance and effective focal zone measurement techniques and electronic characteristics of ultrasonic C-scan equipment.

Reference defects and materials: Identified types of defects encountered and materials and methods used by industry for simulating manufacturing defects and service-induced damage.

Porosity: The assessment considered various ultrasonic attenuation measurement techniques that are used for determining porosity levels. Porosity is defined as a concentration of the microscopic voids that are entrapped in the resin within and between fibre layers. Although there are a number of techniques that can be used to measure relative attenuation, none of these can be relied upon to provide a single, unambiguous measurement of the porosity level. The size distribution and shape of voids cannot be quantified using current ultrasonic techniques. For most quality control requirements, it is sufficient to relate relative ultrasonic attenuation to an acceptance standard (i.e. maximum acceptable porosity level) rather than establish the exact percentage of voids in the material. This approach is universal, although accurate porosity level measurements would be preferable. A level of 1% porosity is generally accepted for most pre-impregnated composite structures, although higher levels are tolerated in certain circumstances. The recommended approach for quantitative void content is to use image analysis techniques. Difficulties encountered in controlling the introduction of porosity make the production of reference materials with known porosity levels impractical.

2.2 PRIOR STATUS OF STANDARDS AND PROCEDURES

It was apparent from contact with industry, that no international or national standard procedures were available for ultrasonic C-scan inspection of composite structures. This situation remains unaltered. Many contributors to the assessment were using written forms of either 'in-house' procedures or procedures specified by customers, the majority of which involved the use of some form of reference material containing typical defects. A number of companies within the aerospace/defence industry are currently using either the McDonnell Douglas Process Standard DPS 4.738-2 [2] or, to a lesser extent, Boeing Aircraft Company Process Specification Number BAC5980 [3]. Both documents specify process requirements and provide instructions for the ultrasonic inspection of composite structures.

The scope of the procedures in use covers a wide range of ultrasonic C-scan applications, from contact to immersion probes, with straight or angled beams, for a frequency range of 0.4 to 20 MHz. The procedures are suitable for examining flat panels and honeycomb sandwich constructions for single- and double-through transmission, and pulse-echo modes of operation. Only a few documents relating to calibration of transducers and associated electrical drive systems were directly relevant to the ultrasonic C-scan inspection of composites, such as the McDonnell Douglas document and ASTM E 1065-92 [4]. The latter is a "guide" containing detailed experimental evaluation techniques, but no tolerances. It does, however, consider the transducer in isolation, rather than the transducer/transmitter combination or even the complete ultrasonic C-scan system. The McDonnell Douglas document considers systems as a whole, with few specifications for transducers alone. It is the only procedure that directly addresses the C-scan inspection of composites.

The work led to the development of three working draft procedures which were the subject of a UK round-robin validation reported here, which will be followed by an international round-robin to generate world-wide support for the procedures.

3. ULTRASONIC C-SCAN PROCEDURES - WORKING DRAFTS

Three working draft procedures for 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" [5-9].

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 either a continuous or discontinuous format; including 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.

(a) Attenuation measurements

Attenuation measurements were carried out on a range of materials, these included Perspex™, stainless steel, glass-fibre woven fabric composites and the carbon-fibre reinforced reference panel (see Figure 1). The objective was to produce a method for determining absolute attenuation. The results have been included as part of the operational procedure. This work involved identification and quantification of systematic uncertainties in amplitude and defect size measurements due to diffraction and refraction effects, peak-frequency downshift and non-linear propagation in water [5]. A procedure was developed that enables the bulk attenuation coefficient ($dBmm^{-1}$) to be calculated for the frequency used and as a function of frequency ($dBmm^{-1}Hz^{-1}$) [6].

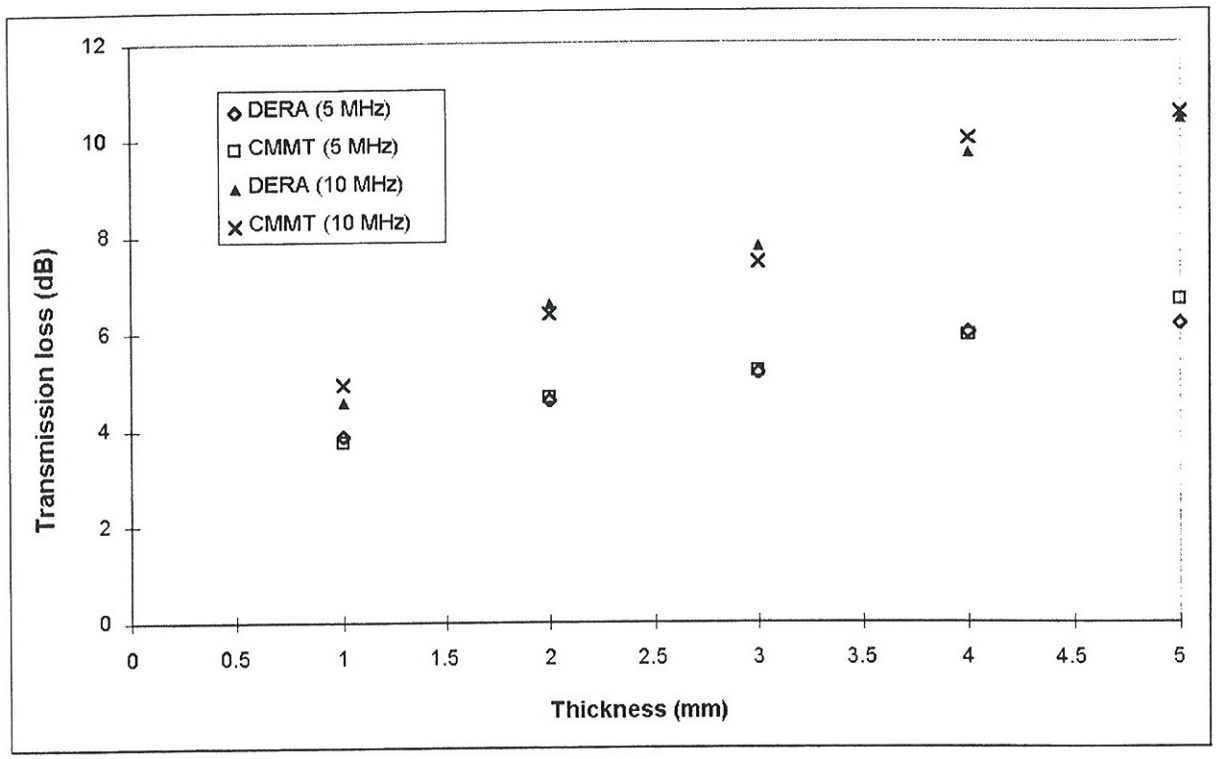


Figure 1 Transmission loss vs thickness for stepped CFRP laminate.

(b) Transducer calibration procedure

Calibration procedures were developed for NDE ultrasonic transducers using hydrophones and pulse-echo methods (i.e. spherical and flat targets). The experimental assessment considered the effect of collimators on beam parameters. A series of tests were carried out to evaluate the effect of changing collimator aperture size, thickness and collimator-transducer stand-off distance. The enhancing effect of placing a PTFE collimator in front of an unfocused transducer is shown in Table 1. The results demonstrate that for a 10 MHz transducer with a crystal diameter of 10 mm, a 4 mm diameter aperture reduces the -3 dB bandwidth (as measured using membrane hydrophones) by a factor of 3 and the position of the last axial maximum (Yo^*) by an order of magnitude.

Ultrasonic wave properties (i.e. attenuation and phase velocity) were measured for a number of isotropic and anisotropic materials in order to assess the effect of dispersion, frequency downshift and non-linear propagation on ultrasonic measurements. The addition of a collimator with an aperture smaller than the crystal diameter of the transducer results in a cleaner and more symmetric beam, albeit at the expense of the beam energy. The results have been included as appendices in the draft calibration procedure.

Table 1 Effect of collimator on 10 MHz frequency/10 mm diameter transducer

Parameter	Uncollimated	4 mm Diameter Collimator
Position of last axial maximum ,Yo^* (mm)	140	15
- 3dB beamwidth (mm)	3.3	1.0

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.

(a) Manufacture of a reference panel

A stepped reference panel manufactured from carbon fibre-reinforced epoxy was circulated to a number of companies within the UK to compare the systems currently in use, prior to standardising on a common procedure. The objective of the R-R exercise was to identify the key parameters which influence inspection quality and to establish the degree of control required to obtain suitable repeatability and accuracy. The reference panel (Figure 2), 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 $[45°/0°/-45°/90°/90°/-45°/0°/45°]_S$. 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.

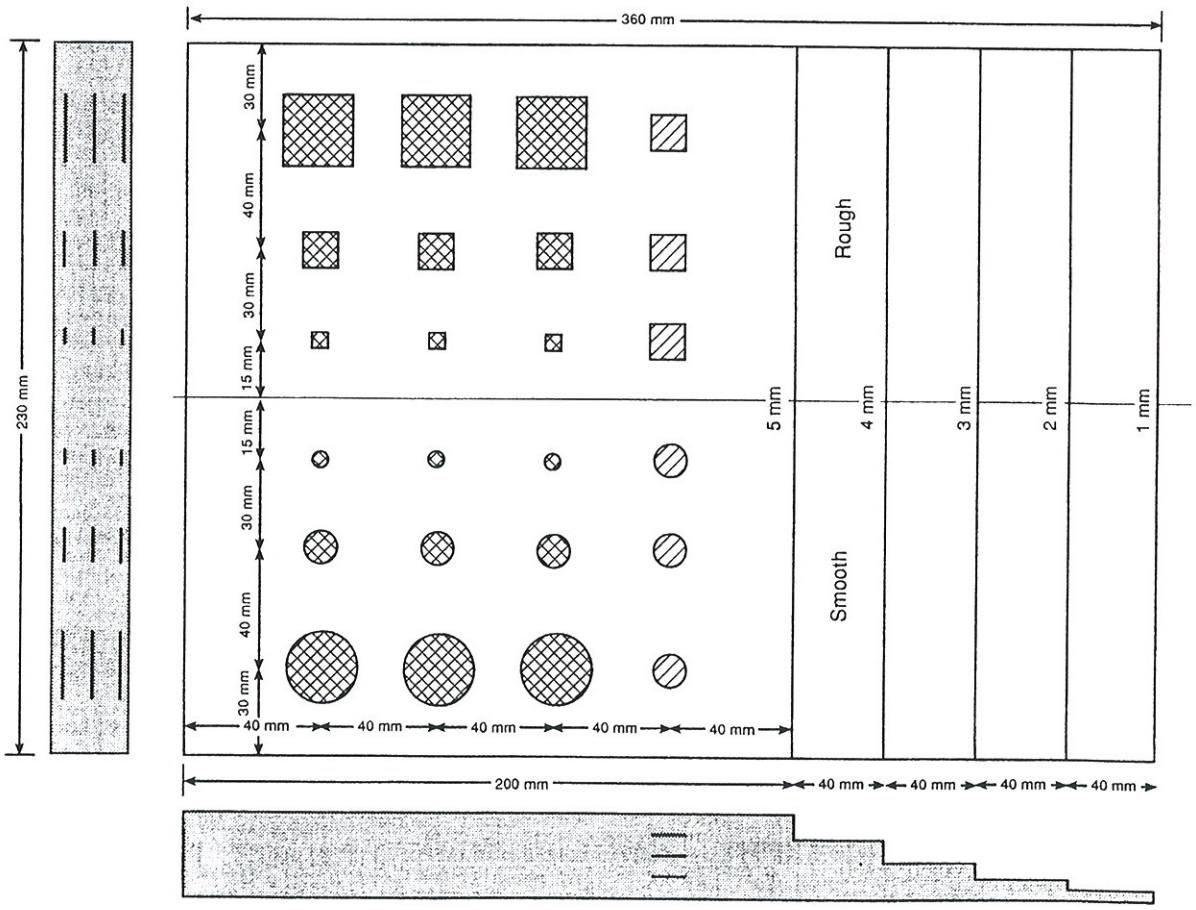


Figure 2 Stepped laminate panel with circular and square inserts.

Artificial defects (representing delaminations) 6.35, 12.7 and 25.0 mm in size were fabricated using two layers of 50 μm thick poly-tetrafluroethylene (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 2), at the mid-plane (second row from top in Figure 2) and between the 38th and 39th plies (third row from top in Figure 2) 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 (see above). The inserts, 12.7 mm in size, were located as shown in Figure 2 (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 3.

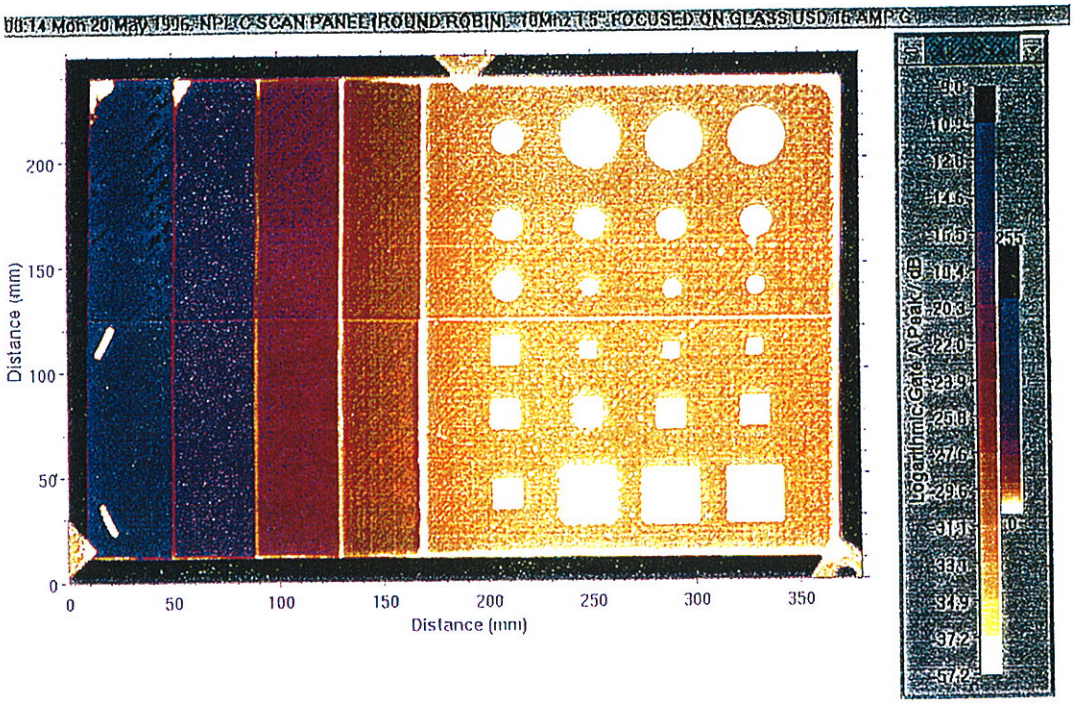


Figure 3 C-scan image of stepped reference panel with defects (courtesy of DERA).

4. ROUND-ROBIN RESULTS

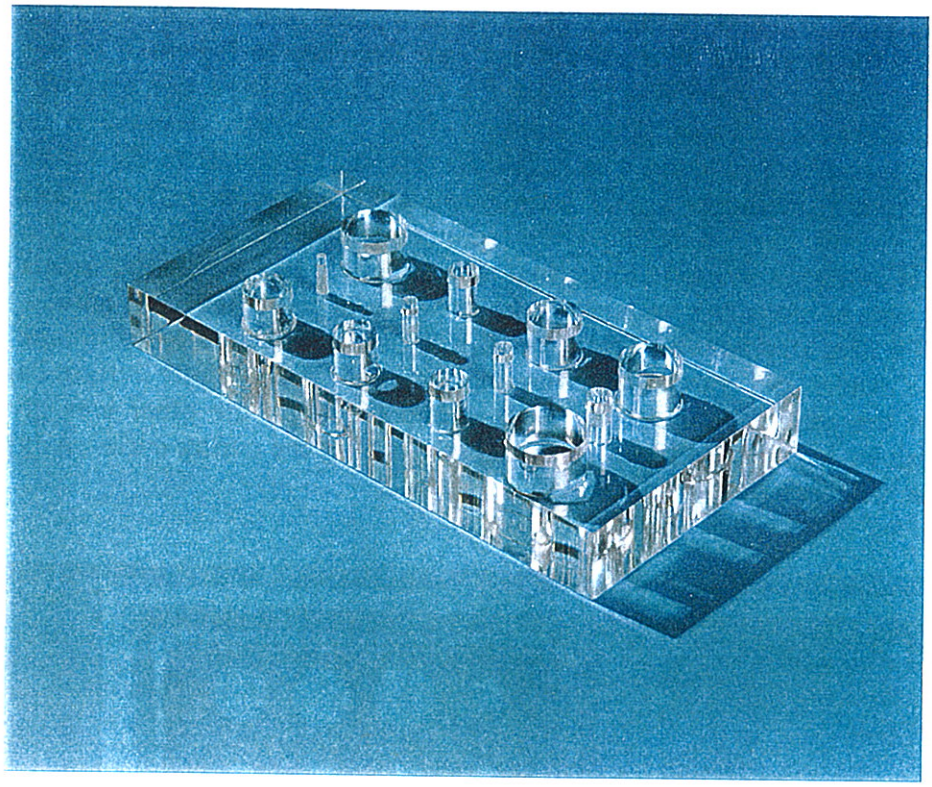


Figure 4 Perspex™ test block with raised cylinders of known diameter.

The same panel used in the research programme was re-circulated. In this second exercise, each participant was required to inspect the panel using the operational procedures developed within the programme (cf using their own procedures in the research phase). The draft procedures were accompanied by a check list to assist in the evaluation. A Perspex™ test block (Figure 4) incorporating raised cylinders covering a range of diameters was used to check defect sizing errors for defect gated scans. The ends of these cylinders were machined flat to the same height. These cylinders behave as disc reflectors of known. Participants were requested to carry out absolute attenuation measurements on the stepped reference panel and to size the defects for both the reference panel and the Perspex™ test block according to the -6 dB defect sizing method, where possible. A similar exercise has been carried out to assess the calibration procedures for ultrasonic transducers.

4.1 OPERATIONAL PROCEDURES

The majority of the participants were unable to size the defects using the -6 dB method [11] or measure absolute attenuation due to software or hardware limitations. Tables 2 to 5 show defect size measurements obtained for double-through transmission (DTT) inspection in the X- and Y-directions for double-layered inserts located between the 2nd and 3rd plies (upper-plane), at the mid-plane and between the 38th and 39th plies (lower-plane) of the stepped panel. Table 2 shows DTT measurements obtained by the same participants for the single-layered PTFE film inserts. Participants 1 and 2 used 10 MHz focused transducers and Participant 3 used a 5 MHz focused transducer. Appendix 1 shows typical C-scan images obtained for the stepped reference panel.

Table 2 R-R results - upper-plane double-layered defect dimensions (mm) for DTT

Insert width/diameter	Participant 1		Participant 2		Participant 3	
	X	Y	X	Y	X	Y
Square insert						
25.1 mm	26.4	26.4	25.0	24.0	26.0	27.5
12.7 mm	13.3	13.2	12.0	14.0	13.5	14.0
6.35 mm	7.0	6.9	6.0	7.0	6.5	7.5
Circular insert						
25.1 mm	26.3	26.3	22.0	24.0	25.5	27.5
12.7 mm	13.8	13.8	13.0	12.0	13.0	14.5
6.35 mm	7.6	7.6	6.0	7.0	7.0	8.0

Table 3 R-R results - mid-plane double-layered defect dimensions (mm) for DTT

Insert width/diameter	Participant 1		Participant 2		Participant 3	
	X	Y	X	Y	X	Y
Square insert						
25.1 mm	27.3	25.6	23.0	25.0	27.0	28.5
12.7 mm	13.3	13.1	11.0	10.0	13.0	14.5
6.35 mm	6.6	6.8	6.0	5.0	7.0	8.0
Circular insert						
25.1 mm	26.8	26.8	25.0	24.0	24.0	23.0
12.7 mm	13.6	13.6	12.0	14.0	14.0	14.5
6.35 mm	7.3	7.3	6.0	7.0	6.0	6.0

Table 4 R-R results - lower-plane double-layered defect dimensions (mm) for DTT

Insert width/diameter	Participant 1		Participant 2		Participant 3	
	X	Y	X	Y	X	Y
Square insert						
25.1 mm	26.2	25.7	25.0	22.0	26.5	28.5
12.7 mm	12.3	12.9	11.0	11.0	13.0	14.5
6.35 mm	7.1	6.5	6.0	7.0	6.5	8.5
Circular insert						
25.1 mm	26.2	26.2	24.0	23.0	25.5	28.0
12.7 mm	13.2	13.2	12.0	11.0	14.0	14.5
6.35 mm	7.2	7.2	6.0	6.0	6.0	7.5

Table 5 R-R results - single-layered defect dimensions (mm) for DTT

Insert width/diameter	Participant 1		Participant 2		Participant 3	
	X	Y	X	Y	X	Y
Square insert						
Upper-Plane	12.9	12.9	13.0	13.0	14.0	14.5
Mid-Plane	12.5	12.9	13.0	13.0	14.0	14.5
Lower-Plane	12.4	12.6	13.0	16.0	14.0	14.0
Circular insert						
Upper-Plane	13.4	13.4	13.0	11.0	14.0	14.5
Mid-Plane	13.1	13.1	13.0	13.0	14.5	15.0
Lower-Plane	12.9	12.9	13.0	15.0	14.0	14.5

The following observations can be made from the R-R results on the stepped reference panel:

- *All PTFE inserts were detected by the participants with the position of the defects being almost identical.*
- *The apparent defect size was similar for all participants that sized the defects using the -6 dB defect method; independent of the size, shape and through-thickness location of the insert.*
- *Differences in apparent defect size were dependent on the inspection technique, inspection parameters, defect type and the software used to determine the -6 dB width. Both circular and square defect sizes were generally overestimated using the double-through transmission method (Table 2); independent of transducer parameters.*
- *The uncertainty in defect size measurement for the single-layer inserts was much smaller compared with the double-layer PTFE inserts with taped edges (i.e. sealed envelope). The reflection coefficient at the taped edges is significantly reduced. Unfortunately, the decrease in reflection coefficient is close to 6 dB, thus making it difficult to accurately size the defects using the -6 dB method.*
- *Absolute attenuation measurements varied from 1.2 to 2.0 $dBmm^{-1}$ depending on the inspection technique and the transducer frequency. Attenuation coefficients tend to increase with increasing frequency of the inspection transducer. Differences in calibration procedures may also have contributed to variations in absolute attenuation measurements between participants.*
- *Uncertainty in defect size increased with decreasing defect size.*

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. 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 second R-R results show that the relative attenuation measurements between participants are far closer than the previous exercise, where in-house procedures were used.

The results obtained by the participants for the Perspex™ test block are shown in Table 6. A typical C-scan image of the test block is shown in Figure 5. Only two participants attempted to size the disc reflectors using the -6 dB method. The R-R results clearly show that difficulties were encountered in implementing the -6 dB defect sizing method due to software limitations. Further work is still required in this area.

Table 6 R-R results - Perspex™ test block disc reflector diameter (mm)

True Defect Size	Participant 1		Participant 2
	X-direction	Y-direction	
2.98	3.0	3.0	6.0
4.96	4.9	4.9	9.0
6.09	6.1	6.1	10.5
7.99	7.8	7.9	12.0
9.99	9.9	9.9	13.0
12.08	12.1	12.1	16.5
14.04	13.8	14.0	17.5
16.08	16.0	16.0	19.0
17.99	18.0	18.0	22.0
19.90	19.7	19.9	22.0
21.98	21.8	22.0	24.5
25.10	24.8	25.0	30.5

4.2 TRANSDUCER CALIBRATION

A similar exercise has been carried out to assess the calibration procedures for ultrasonic transducers. Two transducers (10 MHz focused and 5 MHz unfocused) were circulated among equipment manufacturers and end users. Tables 7 and 8 provide a comparison between beam and frequency characteristics measurements obtained for the transducers using the calibration procedures and the manufacturers specifications.

Table 7 Beam and frequency characteristics for 5 MHz unfocused transducer

Parameter	Supplier	Participant 1 Pulser High	Participant 1 Pulser Low	Participant 4	Participant 5
Peak Frequency (MHz)	4.60	5.4	4.8	5.4	4.05
-6 dB Centre Frequency (MHz)	4.85	5.3	5.1	5.4	4.25
-6 dB Bandwidth (%)	n/a	39.2	47.6	45.5	23.0
Last axial maximum (mm)	n/a	116	126	n/a	102
X-dir: -6 dB Beamwidth (mm)	n/a	3.2	3.5	n/a	6.88
Y-dir: -6 dB Beamwidth (mm)	n/a	3.6	3.6	n/a	5.61

Table 8 Beam and frequency characteristics for 10 MHz focused transducer

Parameter	Supplier	Participant 1 Pulser High	Participant 1 Pulser Low	Participant 4	Participant 5
Peak Frequency (MHz)	10.9	10.4	12.2	10.7	10.65
-6 dB Centre Frequency (MHz)	10.9	11.0	12.0	10.7	10.7
-6 dB Bandwidth (%)	n/a	34.8	46.9	45.5	29.0
Focal Distance (mm)	n/a	57.8	58.8	n/a	49.0
-6 dB Focal Zone	n/a	20.9	17.7	n/a	34.0
X-dir: -6 dB Beamwidth (mm)	n/a	0.8	0.7	n/a	0.94
Y-dir: -6 dB Beamwidth (mm)	n/a	0.7	0.7	n/a	0.89

The results in Tables 7 and 8 show the performance characteristics of the transducer are dependent on the output level of the drive system and the test method (i.e. pulse-echo or hydrophone based techniques). Adjusting the output level of the Excitation Unit (i.e. drive system) can result in a considerable difference in the measured parameters. It is generally accepted that the interface between the transducer and the drive system is very difficult to standardise, and the same transducer driven by different drive systems will exhibit different performance characteristics. The transducer calibration procedure makes no allowance for the use of different drive systems. Determination of the true characteristics of a transducer independent of the drive system warrants further investigation.

Differences between the results obtained by Participant 5 and those obtained by Participants 1 and 4 are partially related to the different measurement techniques used to determine the frequency and beam characteristics of the two transducers. The former used hydrophones whereas the latter used the pulse-echo technique.

Polar and radial pulse-echo scans indicate a symmetric beam is generated by the 5MHz unfocused transducer, whereas results from the 10 MHz transducer indicates possible beam splitting and characteristics of a slight squint. Possible causes of the beam split are crystal debonding from the backing material or a crack in the crystal. According to the participant who observed these faults, these characteristics would render the transducer unacceptable for inspection of composite components.

A number of additional editorial and technical comments have been supplied by the participants. The majority of these comments will be included in the final draft procedures.

4.3 REFERENCE PANEL AND SIMULATED DEFECTS

Non-parallel faces in the reference panel caused problems to the operators, in particular when carrying out attenuation measurements on the 4 mm thick step. It was suggested that only spot measurements with normalisation before each measurement would overcome this problem. The current procedure for producing reference panels recommends hardened stainless steel caul and base plates with a flatness of 0.05 mm or less and of sufficient thickness (at least 7 mm) to prevent distortion of the laminate during the curing process.

It was commented that the placement of defects at the mid-plane was not suitable for validating the -6dB defect-sizing method using the back-wall echo-gating technique. This was because a mid-plane defect has a double-pass reflection signal coinciding with the back-wall signal. Hence, a back-wall echo-gated scan will still show a signal in the gate at the defect location where no signal should be present, demonstrating the problems associated with detection of defects along the mid-plane. The near surface defects can also be difficult to detect due to interference with reflection with front surface signal reflection. It was recommended that additional defects be located at one quarter of the thickness to give a more suitable range of detectability.

Difficulties were experienced when trying to use the 6dB drop method to locate the edge of the double-layered sealed PFTE inserts (i.e. delaminations). These artificial defects have taped edges which result in a considerable reduction in the reflection coefficient. Unfortunately, the drop in the reflection coefficient is close to 6 dB. This introduces a very large uncertainty in the positioning of the -6 dB point at the edge, particularly for defect-gated scans. The effect is to underestimate the defect size for defect-gated pulse-echo scans and to slightly overestimate the defect size for back-wall echo-gated pulse-echo or DTT scans. It was recommended that further consideration be given to the construction of double-layer defects; possibly using a thicker single layer in preference to the sealed envelope insert. Alternatively, hot sintering of the edges could be undertaken using a hot press. Signal drop across single layer defects was often less than 6 dB, thus posing problems in using the -6 dB defect sizing method. As the inadvertent inclusion of peel ply is a common occurrence, the factors (e.g. transmission through the defect or diffraction effects) that affect sizing measurement need further examination.

5. CONCLUDING REMARKS

A number of methods (e.g. absolute attenuation and defect sizing) within the operational draft procedure will probably need to be simplified and be more prescriptive in order to encourage the uptake of the procedures and to maximise the benefits to industry. Future work concerns the wider adoption of the C-scan procedures by industry through their development as national or international standards. The stepped reference panel will be sent to a number of companies throughout Europe (e.g. DASA) and in the USA (e.g. Boeing/McDonnell Douglas) to be scanned using the NPL draft procedures. The results from the national (Phase 1) and international (Phase 2) validation exercises are to be used to improve the working draft procedures which have been submitted to the British Standards Institution (BSI) for consideration as a new work item (NWI) for CEN or ISO standardisation. These documents have been processed into Comité Européen de Normalisation (CEN) frame text versions by the technical committee ACE/56 (Testing of Aerospace Metallic Materials), with support from ACE/64 (Aerospace Structural Reinforced Plastics, for submission to AECMA as EN Aerospace standards.

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.

ACKNOWLEDGEMENTS

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The IAG consists of: Aerostructures Hamble Ltd, British Aerospace Airbus Ltd, BNR Europe Ltd, British Aerospace Defence (Military Aircraft), British Airways, Buehler Krautkramer, GEC Alsthom, GKN Westlands (IoW), Hexcel Composites, Hurel Du Bois, Meccasonics Ltd, Rolls Royce and Associates, St Bernards Composites Ltd, Shorts Bros Plc and Ultrasonics Sciences Ltd.

REFERENCES

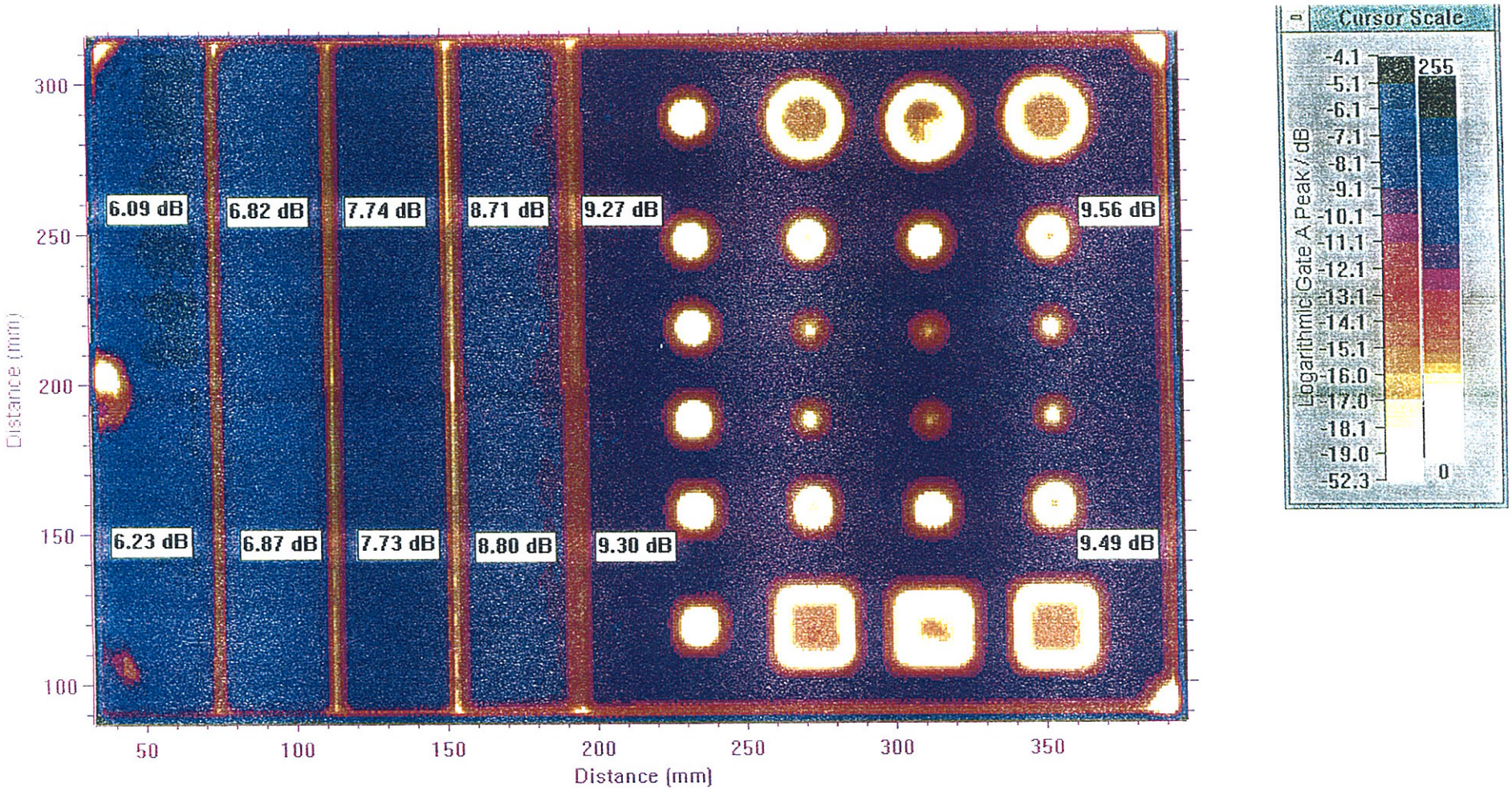
1. McDonnell Douglas Process Standard DPS 4.738-2, "Ultrasonic Inspection of Composite Structures", 1988.
2. Lesniarek-Hamid, J.L. and Sims, G.D., "Standardisation Requirements for Ultrasonic C-Scanning of Polymer Matrix Composites - An Initial Assessment", NPL Report DMM(A)105, 1993.
3. Boeing Aircraft Company Process Specification Number BAC5980, "Non-Destructive Inspection of Composite Parts and Structures", 1981.
4. ASTM E 1065-96, "Standard Guide for Evaluating Characteristics of Ultrasonic Search Units", ASTM Standards, Volume 03.03, Nondestructive Testing, pp 462-480, 1998.
5. Smith, R.A., Zeqiri, B., Jones, L.D. and Hodnett, M., "Nonlinear Propagation in Water and Hydrophone Methods for Characterising Ultrasonic NDT Transducers", INSIGHT, Vol 40, No 1, pp 12-19, January 1998.
6. Smith, R.A., Jones, L.D., Zeqiri, B and Hodnett, M, "Ultrasonic C-Scan Standardisation for Fibre-Reinforced Polymer Composites - Minimising the Uncertainties in Water and its Effect in Attenuation Measurements", INSIGHT, Vol 40, No 1, pp 34-43, January 1998.
7. Zeqiri, B., Hodnett M., Smith, R.A. and Scudder, K.P., "An Assessment of Pulse-Echo and Hydrophone Methods for Characterising Ultrasonic NDT Transducers", INSIGHT, Vol 40, No 1, pp 20-27, January 1998.
8. Zeqiri, B. and Hodnett, M., "A Systematic Investigation of the Effect of Collimators on the Characteristics of NDT Transducers", INSIGHT, Vol 40, No 1, pp 28-33, January 1998.
9. Smith, R.A, Jones L.D., Willsher, S.J. and Marriott, A.B., "Diffraction and Shadowing Errors in -6 dB Defect Sizing of Delaminations in Composites", INSIGHT, Vol 40, No 1, pp 44-49, January 1998.
10. ISO/DIS 1268 - Part 4, Test Plate Manufacturing Method - Moulding of Preimpregnates (using Autoclave, Pressclave, Hydraulic Press and Vacuum Bag Equipment).
11. Smith, R.A., "Ultrasonic Defect Sizing in Carbon-Fibre Composites - An initial Study", INSIGHT, Vol 13, No 8, pp 595-605, August 1994.

APPENDIX 1

C-Scan Results

A.1 Inspection Details and C-Scan (Absolute Attenuation) Results - Participant 1

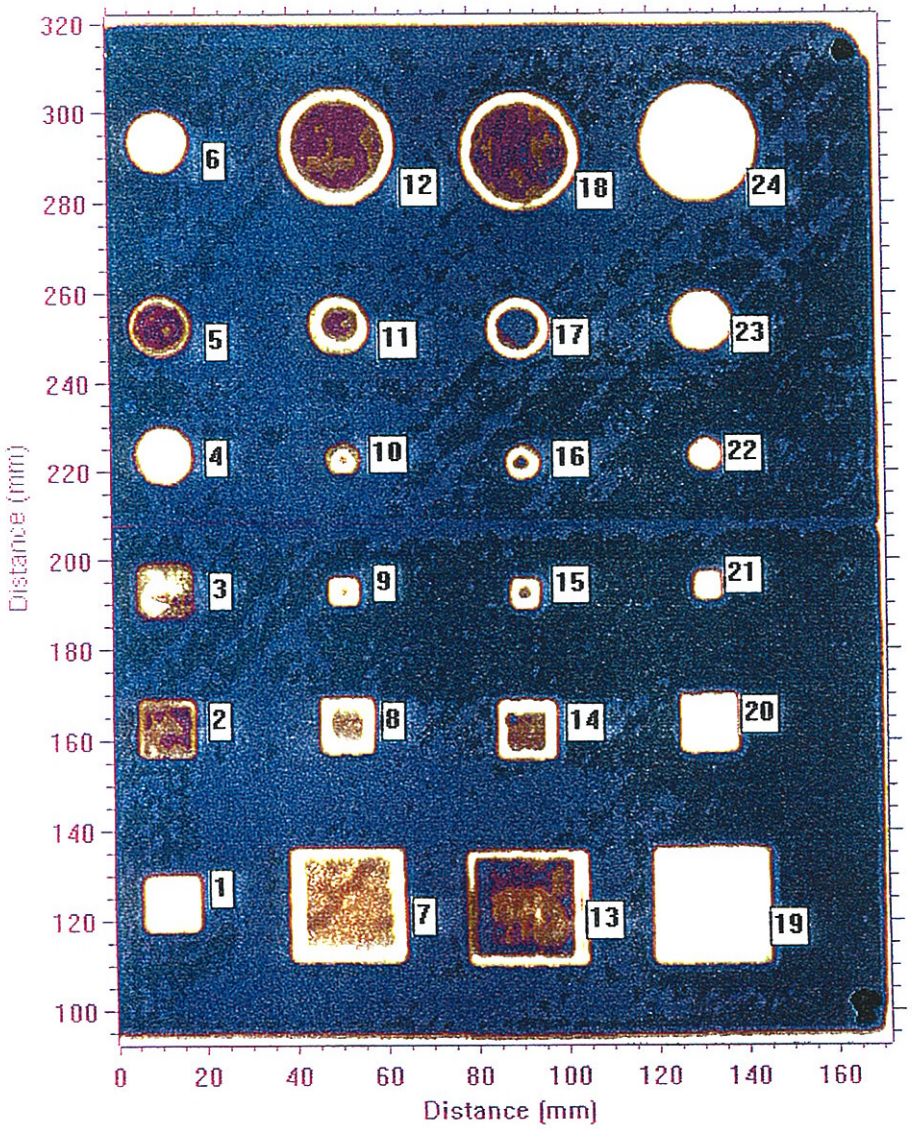
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Operation mode	Double-through transmission
Transducer manufacturer	KB Aero tech Alpha
Transducer type	Unfocused
Transducer size (mm)	12.5
Transducer frequency (MHz)	2.25
Transducer focal length (mm)	Not applicable
Focal spot size (mm)	Not applicable
Collimator material	Not applicable
Collimator internal diameter (mm)	Not applicable
Stand-off distance (mm)	6
Scan index/step size (mm)	0.1
Speed (mm/sec)	100
Reflector	Glass
Temperature (^{o}C)	20.0



ATTENUATION VALUES TAKEN OVER THE AVERAGE AREA
PROBE HAS NOT BEEN RENORMALISED OVER INDIVIDUAL STEPS

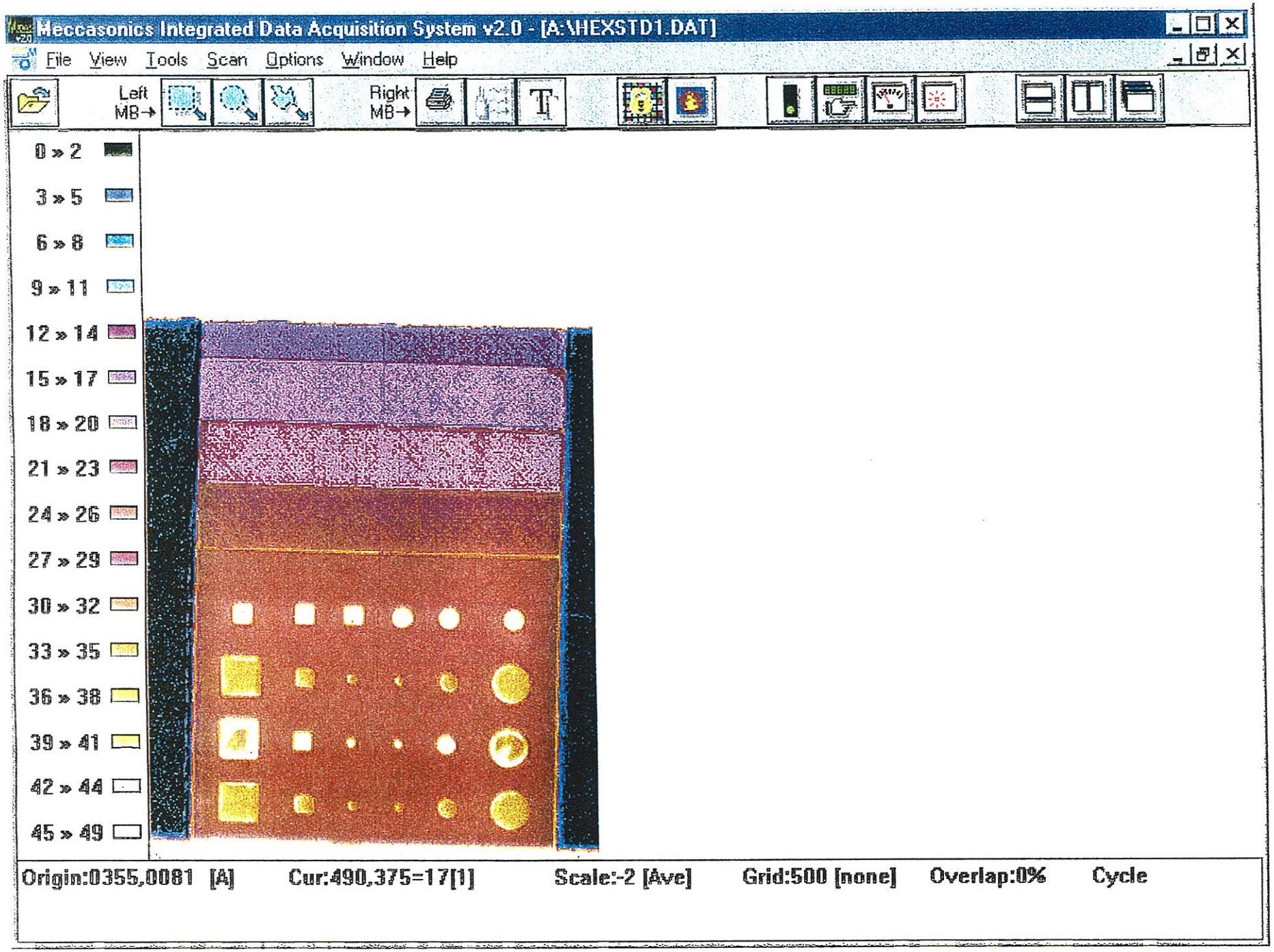
A.2 Inspection Details and C-Scan (Defect Sizing) Results - Participant 1

Transducer Parameters and System Settings	
Scanning system	Meccasonics/Buehler Krautkramer USIP 20
Operation mode	Double-through transmission
Transducer manufacturer	KB Aero Tech Alpha
Transducer type	Focused
Transducer size (mm)	10.8
Transducer frequency (MHz)	10
Transducer focal length (mm)	75
Focal spot size (mm)	Not supplied
Collimator material	Not applicable
Collimator internal diameter (mm)	Not applicable
Stand-off distance (mm)	Not applicable
Scan index/step size (mm)	0.1
Speed (mm/sec)	100
Reflector	Glass
Temperature (^{o}C)	20.3


Distance (mm)
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300
280
260
240
220
200
180
160
140
120
100
0
20
40
60
80
100
120
140
160
Distance (mm)
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2
3
4
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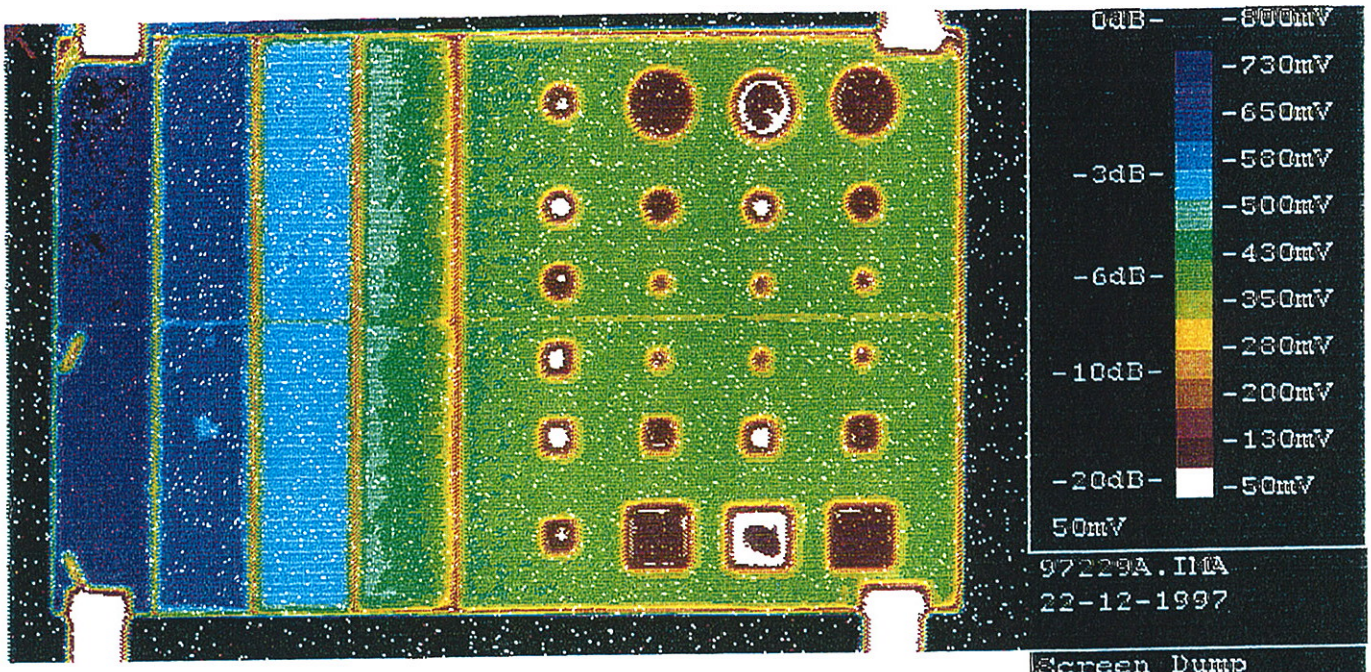
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Operation mode	Double-through transmission
Transducer manufacturer	Meccasonics
Transducer type	Focused
Transducer size (mm)	Not supplied
Transducer frequency (MHz)	10
Transducer focal length (mm)	Not applicable
Focal spot size (mm)	Not applicable
Collimator material	Not applicable
Collimator internal diameter (mm)	Not applicable
Stand-off distance (mm)	Not supplied
Scan index/step size (mm)	0.2
Speed (mm/sec)	150
Reflector	Glass (15 mm thick)
Temperature (°C)	25


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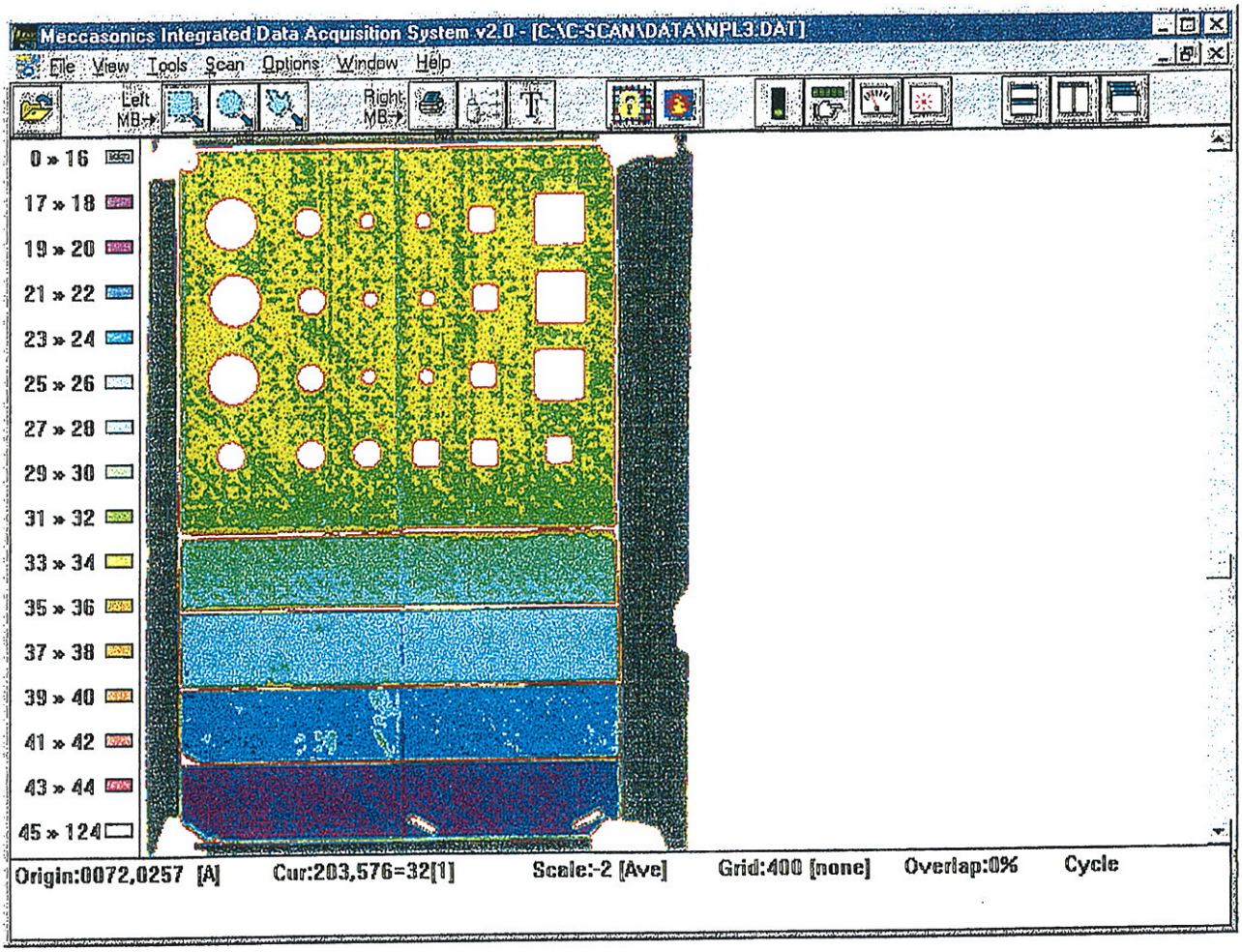
A.4 Inspection Details and C-Scan Results - Participant 3

Transducer Parameters and System Settings	
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Transducer frequency (MHz)	5
Transducer focal length (mm)	Not supplied
Focal spot size (mm)	Not supplied
Collimator material	Not applicable
Collimator internal diameter (mm)	Not applicable
Stand-off distance (mm)	Not supplied
Scan index/step size (mm)	Not supplied
Speed (mm/sec)	Not supplied
Reflector	Not supplied
Temperature (°C)	Not supplied


0dB-
-3dB-
-6dB-
-10dB-
-20dB-
-800mV
-730mV
-650mV
-580mV
-500mV
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-350mV
-280mV
-200mV
-130mV
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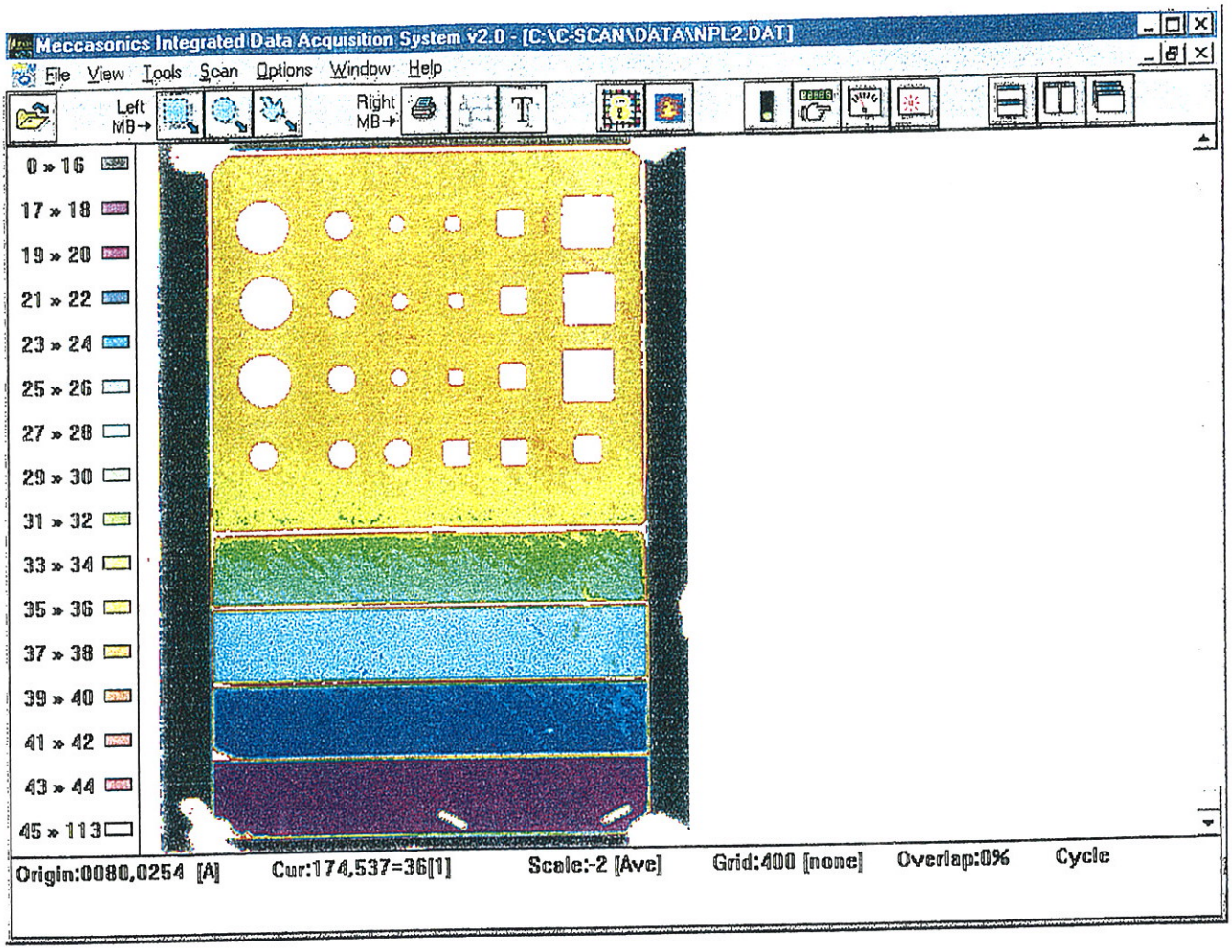
A.5 Inspection Details and C-Scan Results - Participant 4

Transducer Parameters and System Settings	
Scanning system	Meccasonics
Operation mode	Double-through transmission
Transducer manufacturer	Meccasonics
Transducer type	Unfocused
Transducer size (mm)	Not supplied
Transducer frequency (MHz)	5
Transducer focal length (mm)	Not applicable
Focal spot size (mm)	Not applicable
Collimator material	PTFE
Collimator internal diameter (mm)	6
Stand-off distance (mm)	Not supplied
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Speed (mm/sec)	Not supplied
Reflector	Glass
Temperature (^{o}C)	Not supplied


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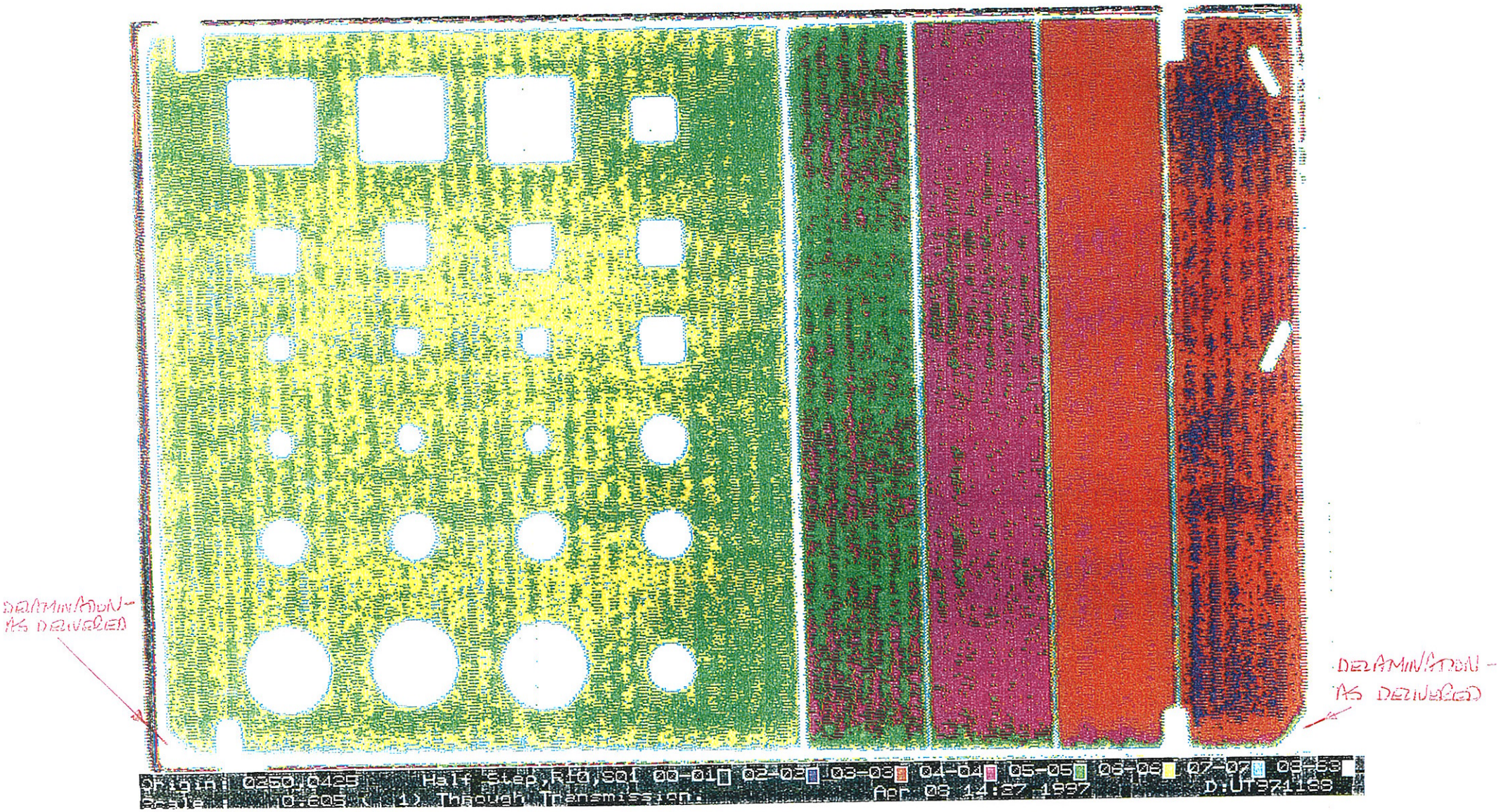
A.6 Inspection Details and C-Scan Results - Participant 4

Transducer Parameters and System Settings	
Scanning system	Meccasonics
Operation mode	Double-through transmission
Transducer manufacturer	Meccasonics
Transducer type	Focused
Transducer size (mm)	Not supplied
Transducer frequency (MHz)	10
Transducer focal length (mm)	75
Focal spot size (mm)	Not supplied
Collimator material	Not applicable
Collimator internal diameter (mm)	Not applicable
Stand-off distance (mm)	Not supplied
Scan index/step size (mm)	0.4
Speed (mm/sec)	Not supplied
Reflector	Glass
Temperature (°C)	Not supplied


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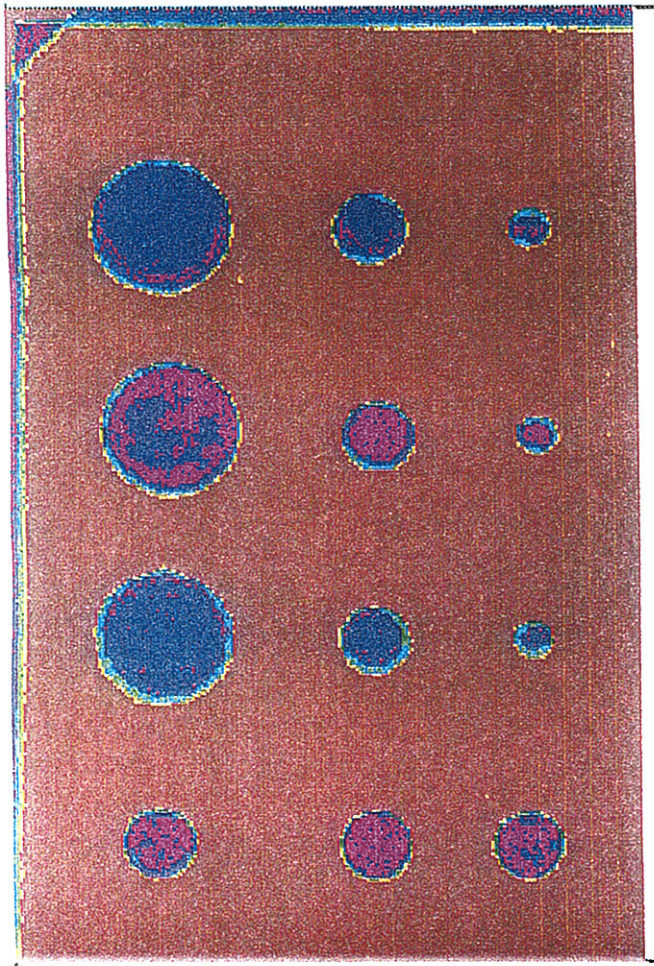
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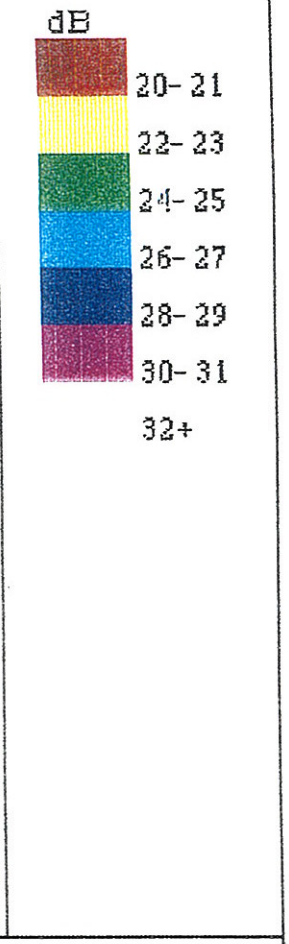
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Operation mode	Single-through transmission
Transducer manufacturer	Meccasonics
Transducer type	Unfocused
Transducer size (mm)	10
Transducer frequency (MHz)	5
Transducer focal length (mm)	Not applicable
Focal spot size (mm)	Not applicable
Collimator material	PTFE
Collimator internal diameter (mm)	6
Stand-off distance (mm)	48
Scan index/step size (mm)	1
Speed (mm/sec)	Not supplied
Reflector	Not applicable
Temperature (°C)	11


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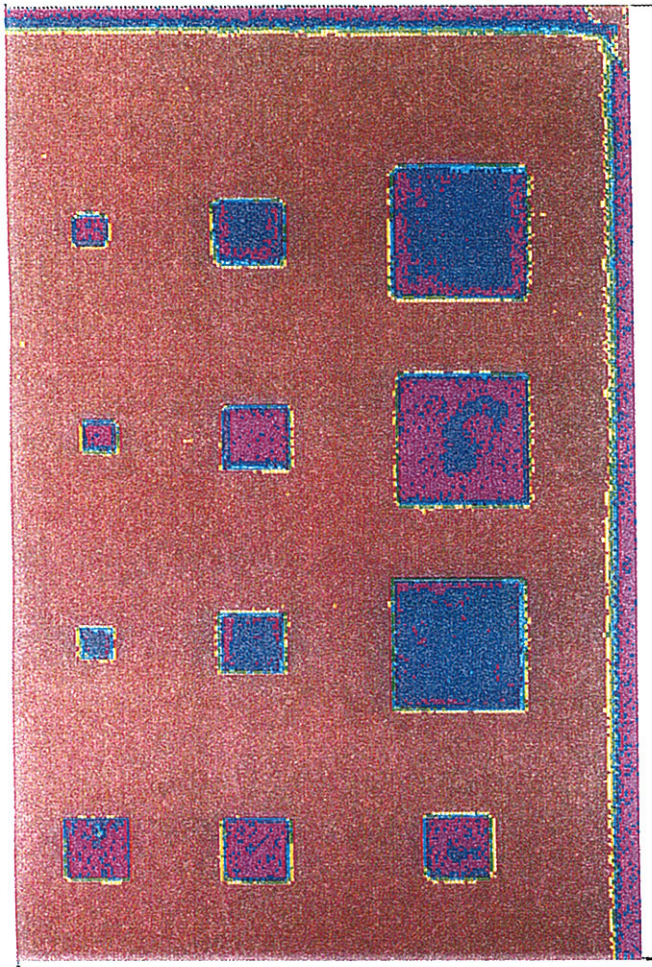
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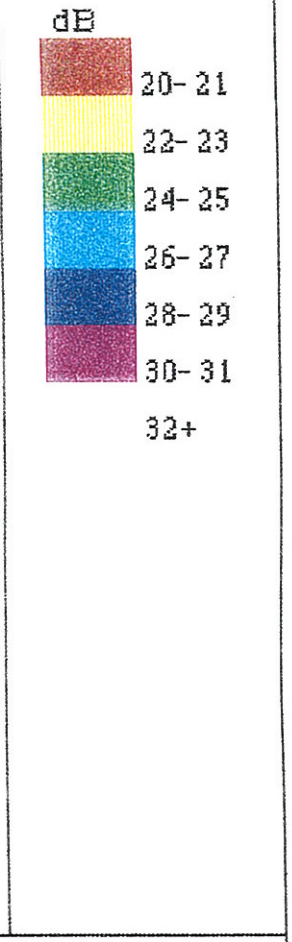
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Scanning system	Harwell
Operation mode	Double-through transmission
Transducer manufacturer	Marconi
Transducer type	Focused
Transducer size (mm)	10
Transducer frequency (MHz)	10
Transducer focal length (mm)	55
Focal spot size (mm)	0.5
Collimator material	Not applicable
Collimator internal diameter (mm)	Not applicable
Stand-off distance (mm)	48
Scan index/step size (mm)	0.4
Speed (mm/sec)	6
Reflector	Glass
Temperature (^{o}C)	16





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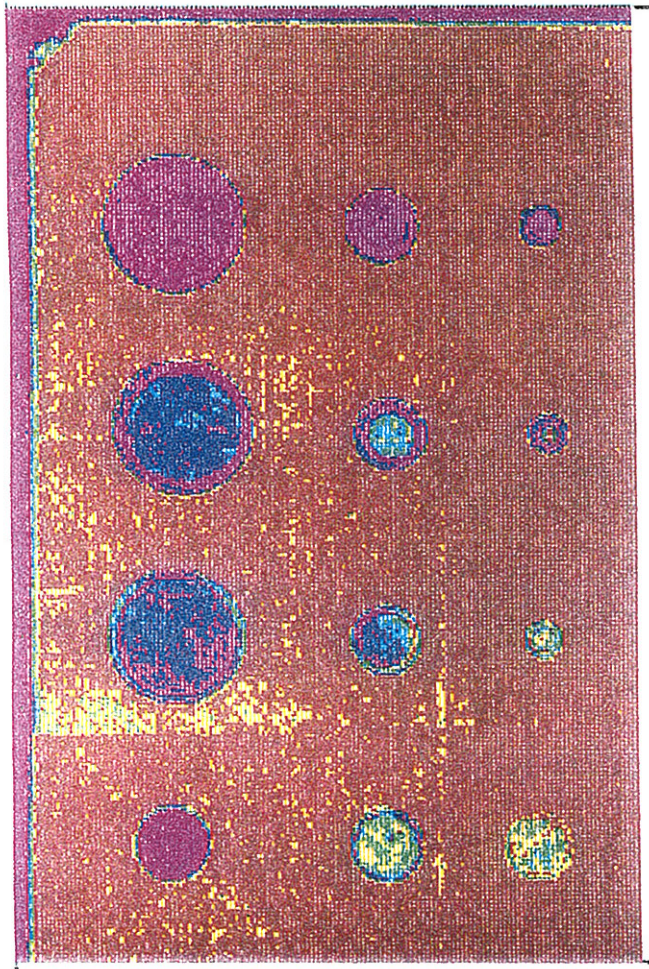


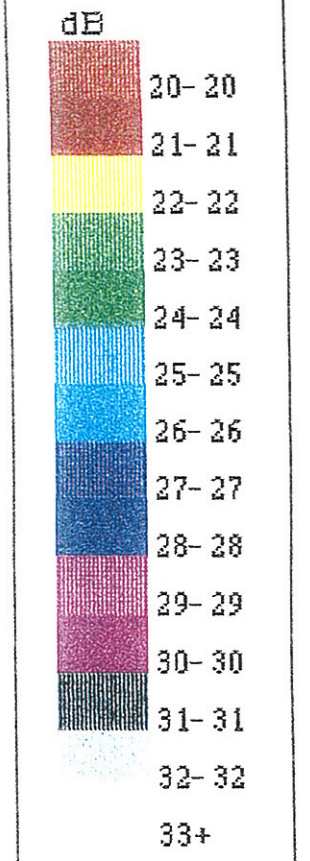


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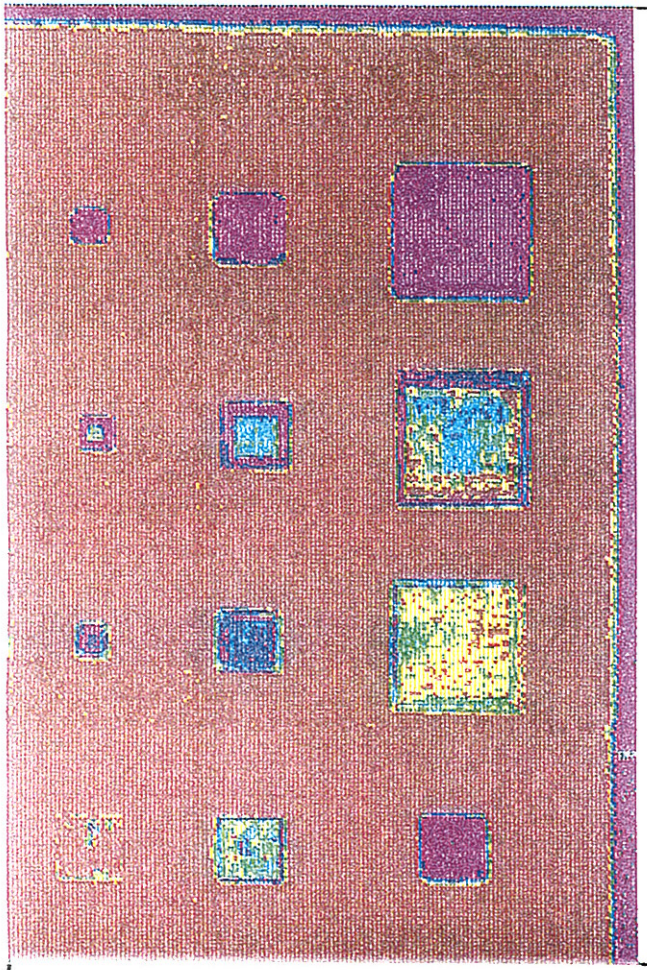
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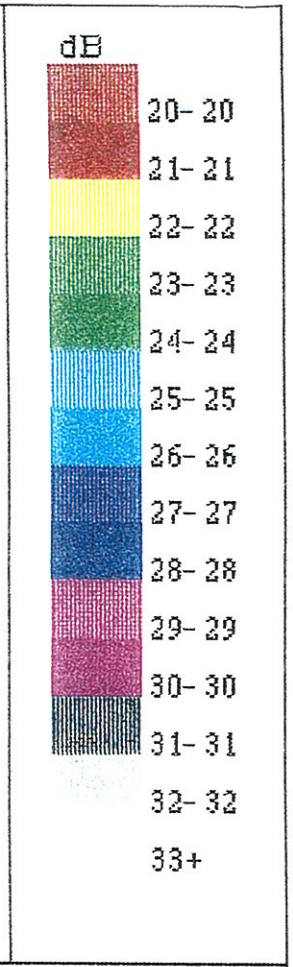
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Operation mode	Pulse-echo
Transducer manufacturer	Marconi
Transducer type	Focused
Transducer size (mm)	10
Transducer frequency (MHz)	10
Transducer focal length (mm)	55
Focal spot size (mm)	0.5
Collimator material	Not applicable
Collimator internal diameter (mm)	Not applicable
Stand-off distance (mm)	Not supplied
Scan index/step size (mm)	0.4
Speed (mm/sec)	6
Reflector	Glass
Temperature (^{o}C)	16





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