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NON-DESTRUCTIVE TESTING – LEARNING FROM THE PAST, MAXIMISING FUTURE BENEFITS.

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In 1997 the Health & Safety Executive instigated a programme to investigate the effectiveness of NDT as applied in industry. AEA Technology managed the Programme for the Assessment of NDT in Industry (PANI) on behalf of the HSE. Twenty operators participated in a round robin exercise to provide a snapshot of the capability and reliability of manual ultrasonic inspection methods currently used in industry. Test pieces which replicated key industrial components were produced containing artificial, service induced defects and these were mounted to simulate on-site access conditions. An ex-service boiler, which had been scrapped because it contained unacceptable defects, was also used as a test piece. The test pieces were sectioned to assist in the analysis of the effectiveness of the ultrasonic inspections. The results show a wide variation in the detection of the defects and in their sizing and positioning. The boiler was particularly challenging.

The presentation will describe how the round robin was planned in order to ensure results relevant to industry. The implementation of the round robin inspections, the details of the test pieces and the analysis of the results will also be discussed. This will provide the background information for a full understanding of the implications of the results which have led to a number of subsequent projects aimed at improving the quality of NDT. These projects have two aims: to add to the pool of data on the capability NDT techniques; to proactively communicate information on NDT capability issues. The progress of these projects will be reported and future benefits for industry highlighted.

Keywords: NDT, manual ultrasonics, reliability

INTRODUCTION

This paper presents the details of the Programme for the Assessment of Non-Destructive Testing (NDT) in Industry (PANI) which was managed on behalf of the Health & Safety Executive (HSE) by the Inspection Validation Centre (IVC), AEA Technology. The programme involved the investigation of current industrial ultrasonic methods for in-service inspection of typical industrial components. At the seminar to launch the PANI programme in June 1997, the HSE stated the objective as follows:
To examine the effectiveness of NDT in assessing the integrity of pressure plant by identifying the components and inspection methods of greatest concern and conducting a round robin exercise.

The reasons for investigating NDT were listed as:
a perceived lack of confidence from industry in NDT
doubts about the capabilities of NDT - the ability to prove 'fitness for purpose' by Engineering Critical Assessments (ECA)
lack of a benchmark or standard to judge these concerns
These reasons were supported by a number of examples of where NDT had failed to detect important defects and plant failures had occurred as a result. These examples involved a range of non-nuclear pressurised components.

There are a number of current trends in plant operation, which increases the importance put on the ability of the applied NDT technique to detect and size defects correctly in order to have confidence in its performance. Companies are looking to reduce costs by extending the life of pressurised plant, adopting risk based inspection, applying non-invasive techniques where possible and subjecting inspection to cost based analysis. In order to extend plant life,

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life cycle analyses are being undertaken and decisions made on the periodicity of inspections. Risk based inspection techniques are being used to focus inspections on key areas of plant. The suitability and capability of the inspections subsequently performed on the key areas of plant are not always known. Non-invasive techniques allow inspections to be performed without opening up vessels or even taking them off line, but again the ability of the proposed technique to detect the defects of concern is not always known or evaluated. Inspections are being subjected to cost benefit analysis but if it is not known how good an inspection is for detecting defects then it is not possible to correctly assess its value.

In response to these industrial trends and in the light of uncertainties over the effectiveness of NDT, the HSE established the PANI project. The aims were to:
determine whether NDT is effective, reliable and repeatable;
eliminate doubts, fears and preconceptions by reducing the uncertainty;
to provide an estimate of NDT capability.
The results would also determine where improvements could be made.

PANI METHODOLOGY

In order to ensure that the programme provided both information and conclusions of direct relevance to industry a PANI Management Committee was set up. The principal industries for the PANI work were:
Steam raising plant using fossil fuels
Gas distribution and storage
Chemical production
Refineries
Oil production
The membership of the committee was taken from these industries and from other relevant organisations. Their remit was to advise the HSE and AEA Technology on the development, implementation and reporting of the PANI project with the purpose of ensuring that the project was aligned with the principal interests of the industries identified above.

An industry questionnaire was used to establish the NDT methods and components for a round robin exercise. The aims of the questionnaire were to gather information from plant owners and industrial inspection companies in order to identify the components and inspections for the round robin exercise. The topics covered by the questionnaire were: Components requiring inspection; Defects of concern; Materials; NDT Methods; Other Issues which covered access, environment etc.

A seminar was used to launch the programme and companies were invited to participate in the round robin. The test pieces manufactured for the round robin exercise were based on the information obtained from the industry questionnaire and were agreed by the Management Committee. The defect types and size ranges were also agreed but the Management Committee had no knowledge of the actual defects in the manufactured test pieces until the round robin inspections had been completed. At the half way stage of the round robin the interim results were considered by the Management Committee and actions agreed. Likewise, the final results were presented to the committee and actions relating to the analysis and presentation of the results, including the format of this report, were decided. At no stage during the project have the Management Committee had access to the results from individual operators.

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DETAILS OF ROUND ROBIN

Based on the results of the questionnaire it was decided that the round robin exercise would look at manual ultrasonics applied to ferritic steel test pieces representative of the components identified above containing typical in-service cracking and erosion / corrosion defects.

Six test pieces were used for the round robin. Five were manufactured and one was an ex-service Cochran boiler. Five test pieces were manufactured containing artificial but realistic defects. The test pieces are summarised in Table 1.

The wall thickness ranged from 7 mm in the nozzle test pieces to 30 mm in the Tee piece. The material was carbon steel plate to BS4360 43A or equivalent and carbon steel pipe ST52. All the welds were manual metal arc with the exception of the upper vee on the longitudinal vessel weld which was a submerged arc weld. All the welds contained defects except for the pipe to pipe weld which was manufactured with deliberate mis-alignment. The types of weld defect are summarised in Table 2. The cracks were elliptical in shape and the lack of fusion defects were rectangular.

Table 1 Outline Details of the Manufactured Test Pieces

Test Piece Identification	**Description**
P1	Thin section set on nozzle with partial penetration weld.
P2	Thin section set through nozzle.
P3	Tee joint with unfused land in the middle of the weld.
P4	Longitudinal double vee vessel butt weld.
P5	Section of pipe and bend containing pipe to pipe, pipe to component and pipe to elbow welds.

In addition, two areas simulating wall thinning by erosion were inserted on the extrados of the pipe bend. Each of the defects in the manufactured test pieces was destructively examined to establish the actual morphology and height.

EX-SERVICE BOILER TEST PIECE

An ex-service Cochran Wee Chieftain Package Steam Boiler was also obtained for use as a round robin test piece. This boiler had been taken out of service because ultrasonic inspection had detected cracking in the front furnace tube to tube plate joint. The inspectors report recorded a maximum crack depth of 3-5 mm depth and 740 mm long about the Bottom Dead Centre position. The SAFed guidelines for the inspection of such boilers require 100% inspection of the internal welds such as the furnace tube to tube plate weld and 20% of the Shell to Tube Sheet welds. For the purposes of the round robin the inspections were restricted to 100% front furnace tube to tube plate joint and four areas of the front shell to tube plate

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weld meeting the 20% requirement. Following the inspection, two pieces were flame cut from the furnace tube of the boiler. These were taken about the 0 mm (Top Dead Centre) and the 800 mm (near Bottom Dead Centre) positions. These pieces were in turn cut at various positions to give the results described below. As the inspection results from the boiler shell to tube plate weld did not give a consensus on the position of any one defect, no sections were taken from this weld.

The objective of the PANI programme - " To examine the effectiveness of NDT in assessing the integrity of pressure plant…" - required that the inspections be performed in a realistic environment. Whilst no attempt was made to mimic the noise and dirt of many inspection environments, the test pieces were arranged so that the operators faced realistic access difficulties.

Table 2 Summary of Defects in Manufactured Test Pieces

Type of Defect		**Total Number**
Lack of Fusion		5
Rough Cracks		11
	Embedded (associated with unfused land)	6
	Far surface breaking	5
Smooth Cracks		7
	Near surface breaking	5
	Far surface breaking	2
Root Erosion Defect		2
Total		25

20 operators were offered by their companies for participation in the round robin. The years spent in NDT by the operators ranged from 5 to 25 with an average of 15. All operators held a PCN Level II qualification in ultrasonics. Eight of the operators held certificates in plate, pipe, nozzle and node categories whilst 5 held the critical sizing qualification. The ultrasonic procedures used by the operators were either a standard ultrasonic procedure, which had been produced by AEA Technology and approved by the Management Committee, or their own company procedures. All the procedures were basically the same, based on the now obsolete BS3923 Part 1, and used a sensitivity of 14 dB below a DAC (Distance Amplitude Curve) based on a 3 mm ∅ SDH (Side Drilled Hole).

RESULTS

The analysis of the results falls into two parts: the results obtained from the manufactured test pieces which contained known discrete defects which allowed for a general analysis of the performance of the operators in detecting the defects; the results from the boiler which can only be compared to discrete destructive analysis.

Although the round robin was principally aimed at the application of manual ultrasonics, it is common industry practice to apply magnetic particle inspection prior to any ultrasonic inspection. Five surface breaking smooth cracks in the manufactured test pieces were detectable with MPI. 72 MPI operator / defect interactions were achieved and only one failed to report a defect.

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On the simple geometry of the vessel weld, test piece P4, the operators performed well giving the detection results shown in Table 3. The ultrasonic inspection of the set-on nozzle, test piece P1, was particularly challenging with the thin wall of 7 mm and an unfused land. The old British Standard gave a lower limit of 8 mm and so strictly speaking the procedure was not valid for this test piece. In the remaining test pieces there were 3 defects which could be said to be very difficult to detect with the techniques applied. So removing these 3 defects with the 4 defects in test piece P1 gives the operator performance shown in Figure 1 for the remaining 13 defects. The detectability of the individual defects in this reduced population is shown in Figure 2.

Table 3 Detection of Defects in Vessel Weld

Defect	Defect Height & Details	Signal Amplitude Above Recording Threshold	No of Operators Who Inspected Defect	No of Operators Who Detected Defect	Detection Frequency For Operators Who Inspected Defect (%)
2	3.0 mm vertical rough crack at weld root	18 dB	20	20	100
3	8.3 mm vertical rough crack at weld root	17 dB	20	20	100
4	3 mm LOSWF 55^{o} tilt	25 dB	20	19	95

Looking at the total defect population of 20 defects, detectable by ultrasonics and not MPI, gives the ultrasonic operator detection rates listed in Table 4 and illustrated in Figure 3. The diagram gives data from 16 operators who were able to inspect most of the test pieces. One of the 16 did not inspect one test piece and his score is adjusted accordingly to give a percentage of the possible defects that he could have detected. The highest detection rate of 70% was achieved by three operators: this equates to the detection of 14 of the possible total of 20 defects. Conversely, the low detection rates of 30% and 35% equate to the detection of 6 and 7 of the 20 defects respectively.

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Table 4 Operator Performance In Detecting Defects With Ultrasonics in Manufactured Test Pieces

No of Operators	No of Defects Inspected with Ultrasonics by these Operators	No of Defects Detected by these Operator	Percentage of Inspected Defects Detected. (%)
1	20	6	30
1	20	7	35
1	20	8	40
1	20	9	45
4	20	11	55
1	20	12	60
1	18	11	61
3	20	13	65
3	20	14	70

The detectability of individual defects in the 20 defect population is illustrated in Figure 4. Two defects were detected by all operators whilst at the other end of the scale three defects were only detected by single operators. False calls were few and appeared random.

Apart from the occasional measurement, the positioning of the defects and the length and height measurements show a spread typical of most studies using a variety of operators. A plot of measured height against actual defect height is shown in Figure 5. Note that a number of points on the plot are positioned on top of each other. The solid line is the best fit line obtained through regression analysis. This has a slope of 0.24 and an intercept of 2.7. The dashed lines above and below show the 95% limits. The ideal line would have a slope of 1 and an intercept of 0.

The results of the inspections of the vessel shell to tubeplate welds did not produce a common consensus of defect positions. However, the inspection of the furnace tube to tubeplate weld showed clearer evidence of the presence of defects. Of the 18 operators who inspected the furnace tube to tube plate weld, 11 reported a defect at the 800 mm (approximately Bottom Dead Centre) circumferential position, three reported unfused land only, one only reported defects at other circumferential locations and two were unable to make sense of the echoes from the weld geometry and therefore didn't report any indications. The final operator was only able to scan with the 0^o probe and therefore only reported unfused land.

At the 0 mm (approximately Top Dead Centre) circumferential position the reports from five operators indicated that a defect might be present. This includes reporting an intermittent defect around the full circumference. The destructive analysis showed that there was weld undercut with associated minor cracking to a depth of 2 mm at the 800 mm region and only minor cracking less than 1 mm in the 0 mm region.

DISCUSSION

Overall it may be concluded that defects were not detected for the following factors:

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- ♦ The defect had a low response or a response which was hard to distinguish amongst other geometric echoes.
- ♦ The defect was only short in length and therefore missed if there was any lapse in concentration or gaps in the scanning raster.
- ♦ Human Factors. This is manifested by a multitude of factors including loss of concentration, poor scanning, poor coupling and generally poor technique. Such effects arise from a variety of causes including poor motivation, poor training, adverse conditions for inspection, fatigue and so on.

The detection rates achieved in the round robin, 30 to 70%, appear poor compared to the results of the PISC III Action 7 inspections which showed detection rates of 67 to 96%. However, the latter were obtained on a test piece 600 by 500 by 100 mm with a double V weld prep. The defects were crack like, vertical and parallel to the weld centre line. They were 10 to 15 mm through wall and 20 to 30 mm long. They were therefore 'easier' than the PANI specimens where some of the defect lengths were small compared to the probe width, or distracting geometric echoes were sometimes present. If these differences are taken in to account, then the PANI results are consistent with the PISC III Action 7 results. These PANI results are in line with the NORDTEST conclusion that NDE may be very unreliable and the Finnish observation that detection in simple butt welds is good but that detection in pipe joints, fillet joints and stud welds is poor. The NIL-NDP detection rate of 50% is broadly consistent with the PANI results.

Although a number of the PANI defects were small and challenging, most were above or near to the allowable size for planar flaws in the ASME Section XI ISI code for volumetric examination of ferritic piping. In addition, all aspects of the design of the project, with the exception of the exact defect sizes, were controlled by the Management Committee to ensure that it was relevant to practices applied on site.

The inspections on all the test pieces have shown how important it is to know the possible defect types, positions and orientations in order to be able to reliably detect the defects of concern. Knowledge of the defect parameters allows the procedure to be tailored to the specific requirements of a particular inspection.

Further analysis of the location and size data from the manufactured test pieces by removing the defects detected by MPI and separating the defects by type - root, unfused land and others, does not provide any different information from that shown in the results section. These results are broadly consistent with the NIL-NDP results which showed an average length error of 8 mm with a standard deviation of 24 mm.

Figure 5, the plot of measured defect height against actual defect height shows what other studies have shown, in that small defects are oversized and larger defects are undersized. However, the slope of 0.24 is far removed from the ideal of 1 and compares poorly to data obtained during the Sizewell B validation process which gave best fit lines of slope 0.85 for operators who achieved certification and of slope 0.42 for all operators. The Sizewell B data was obtained on thicker section material and with larger defects. It is likely that the PANI results were skewed by the geometric echoes interfering with the sizing process and the bias towards smaller defects.

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Three operators gave very similar results from P6 the boiler test piece, which in turn corresponded well with the destructive analysis results. One of the three had considerable experience of inspecting this type of boiler whilst the other two had experience of a range of components but not explicitly this type of boiler. No other characteristic such as age, years of experience or qualifications set these operators apart from the others.

The boiler was particularly difficult for the operators due to the geometry and the limited scanning surfaces. Better results are likely to have been achieved if the operators who had not inspected boilers before had received some training on the geometry and had gained familiarity through practice with the echoes both from the geometry and typical defects.

OVERALL CONCLUSION

The objective of the PANI programme was to obtain a snapshot of the current effectiveness of in-service NDT used for a range standard of key industrial plant components. The programme has identified shortcomings in the application of manual ultrasonics on industrial plant an it is recommended that personnel specifying inspections should not assume that the use of general procedures based on a National Standard will necessarily achieve their required level of reliability when applied by operators with general NDT qualifications. Ways of improving the reliability of application of manual ultrasonics should be considered, particularly when non-simple geometries are to be inspected and the structurally important defects are of a similar size to those in the PANI test pieces. These include the following:

- Use of specific training and practice specimens
- Use of inspection aids for scanning and data recording
- Use of improved procedures and techniques tailored to the specific geometry and defects
- In addition to the above measures aimed at improving the reliability of individual inspections, the use of multiple, independent inspections should be considered to reduce the effect of random human errors. This is particularly pertinent when complex geometries are involved.

THE IMPACT OF PANI

The results of the PANI project have generated a great deal of interest both within the NDT community and outside. There were two separate issues raised in response to the results: the first was to provide quantified information on the benefits to be obtained by adopting the various suggestions for improving the reliability of inspection whilst the second was to communicate the issues to be considered when buying in manual ultrasonics to the personnel on the periphery of NDT. The Health & Safety Executive have responded to these issues by supporting further projects. A document giving Best Practice guidelines has been produced and is available from the HSE web site. Already industry has responded to this best practice document, using them to assist in the procurement of NDT as a whole and using them as an audit tool for their own NDT procurement and application processes. A key detail of the document is the use of NDT operators within a recognised quality system and with technical support through access to a level III qualified person. Work on a Best Practice document for Surface Techniques, MPI and Dye penetrant, has just started.

A proposal for a further round robin exercise which will provide quantified improvements from the various ways of improving inspection reliability is currently under consideration.

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PANI'S IMPLICATIONS ON STRUCTURAL INTEGRITY OF PRESSURISED PLANT

In an Engineering Critical Assessment (ECA) to establish continued fitness for purpose of pressurised components, one of the most important parameters is the dimension of the defect. The PANI project identified that defect detection rate was poor, and when detected, the sizing was inaccurate. These can have serious implications for the validity of an ECA of a component.

The worst detection rate of 26% was for the set on partial penetration nozzle, where operators found it difficult to distinguish between the lack of fusion and the defect. While the geometry of this component made the detection difficult, the external loading on this type of component can be difficult to evaluate, with site pipe fit-up, expansion loads, fatigue cycles etc. contributing to the overall lack of reliable information to confirm continued fitness for purpose.

The best detection rate of 98% was for the butt weld. Of the three defects found by ultrasonic inspection only, two were of 3 mm height, and the other was 8.3 mm high (one third of wall thickness). The three defects were all measured as being between 2 to 10 mm high. In the case of the two 3 mm high defects, only 5% of inspectors undersized one defect, and 16% undersized the other. In the case of the 8.3 mm high defect, 75% of the inspectors undersized it. While it is acknowledged that some inaccuracies will occur, this trend of undersizing the larger defect can have serious safety implications.

The above also calls into question the detection of failure mechanisms such as fatigue. Are the defects detected, and if so are they growing? In the case of a defect in the butt weld, the sizing scatter could disguise crack growth from 2 to 10 mm high if the inspection was carried out with manual ultrasonics at standard intervals.

As stated previously, the general trend in inspection of pressure plant is to extend the period between inspections, use Risk Based Inspection, or Non-Invasive Inspection. These changes to the inspection strategy should be based on the information gained from previous inspections. If the results of the PANI project are considered, the confidence in the results of previous inspections should be carefully evaluated before any major changes in inspection strategy takes place.

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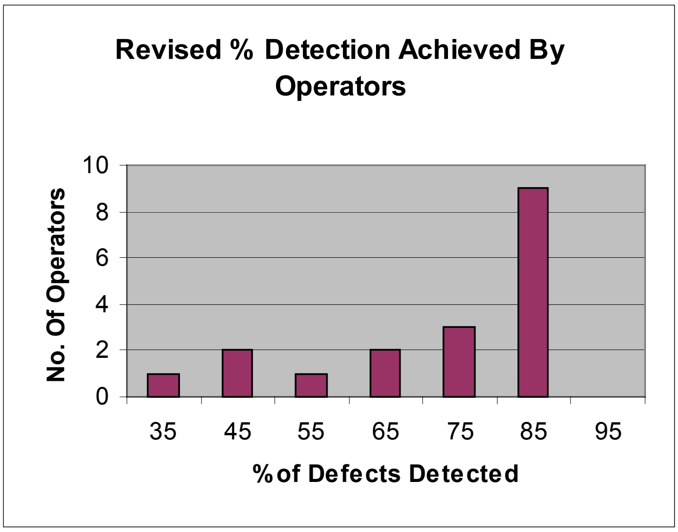

Figure 1 Operator Performance In Detecting Reduced Population of Defects With Ultrasonics In Manufactured Test Pieces

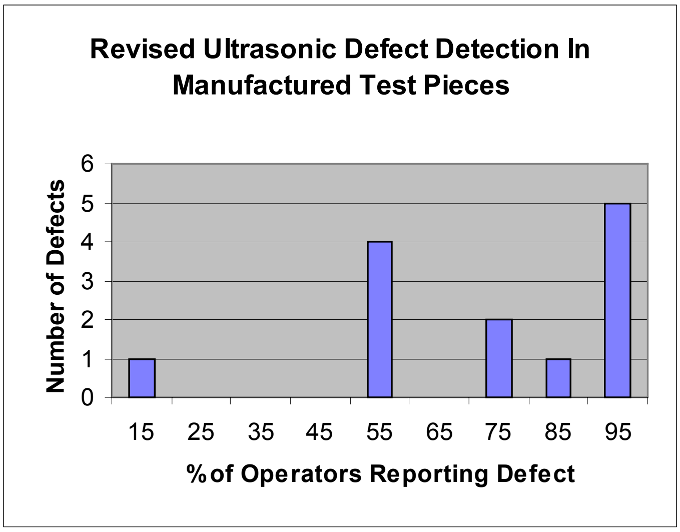

Figure 2 Detectability of Individual Defects In Selected Population of Defects in Manufactured Test Pieces

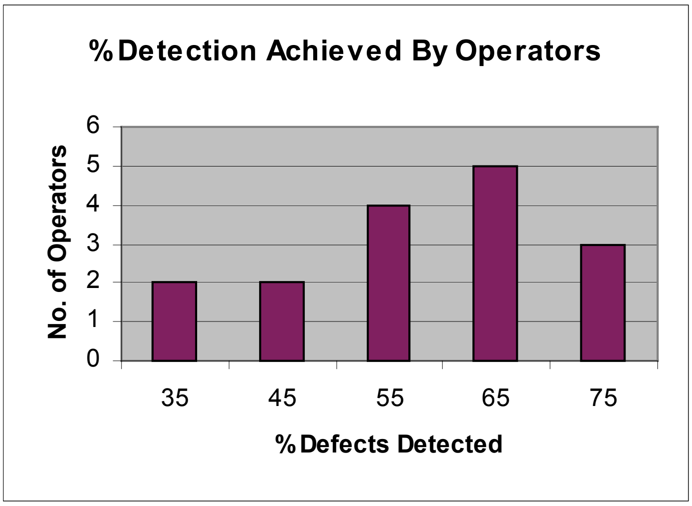

Figure 3 Operator Performance In Detecting All Defects With Ultrasonics In Manufactured Test Pieces

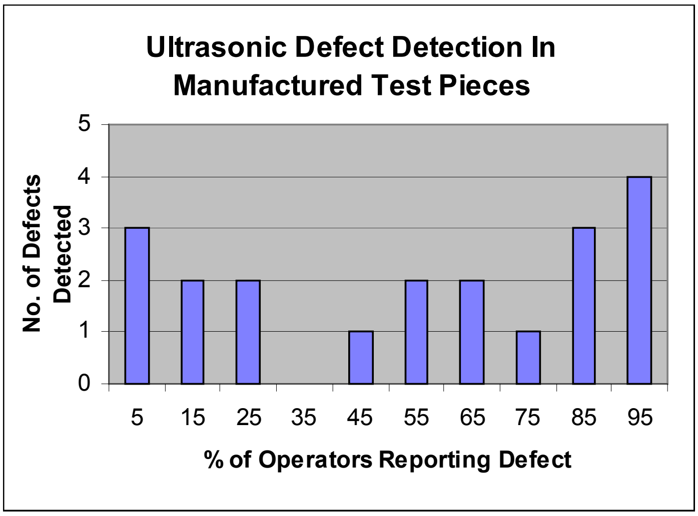

Figure 4 Detectability of All Individual Defects In Manufactured Test Pieces

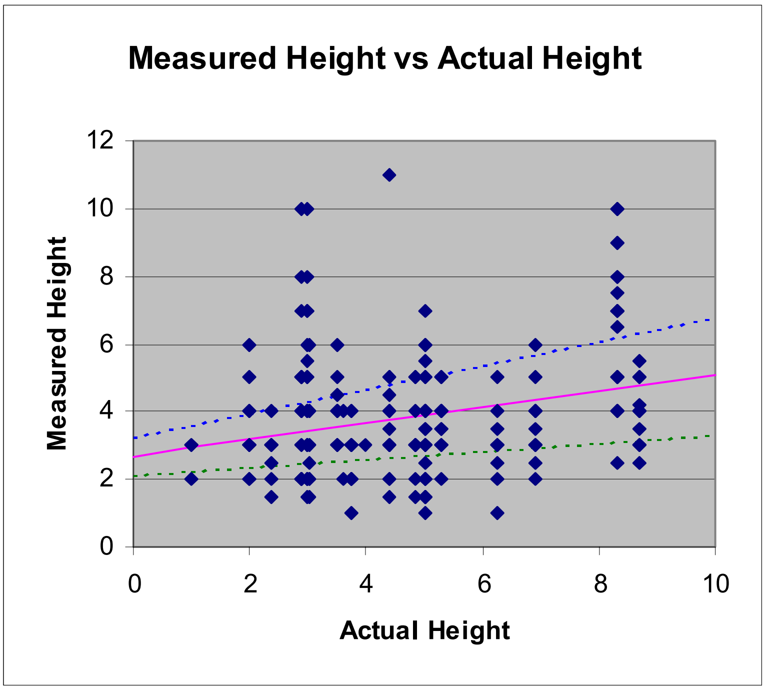

Figure 5 Plot of Measured Defect Height Against Actual Defect Height For The Manufactured Test Pieces