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NESC –1 Inspection Task Group Final Report

PART I:
Analysis Of The Inspection Results From The Pre- and Posttest Round Robin Trials

EUR 19653/I EN

Network for Evaluating Structural Components

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Published by the
EUROPEAN COMMISSION

Directorate-General Joint Research Centre
Institute for Advanced Materials
1755 ZG Petten, The Netherlands

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Printed in the Netherlands

Foreword

The present document is one of a series of reports, which summarise the results of the NESC I project. The complete list of the titles and respective authors is as follows:

Task Group Final Reports

• Inspection (Task Group 1, TG1)	R. Murgatroyd & B. Eriksen
• Materials Characterisation (TG2)	R. Rintamaa
• Thermal and Mechanical Structural Analyses (TG 3)	S. Bhandari & N.Taylor
• Instrumentation(TG 4)	H. Kockelmann & J. Hedderley
• Destructive Examination Advisory Group	J. Hedderly, N. Taylor & P. Minnebo

Project Evaluation Reports

• Constraint	D. Lidbury
• Cladding	R. Bass, C. Faidy & R. Murgatroyd
• Sensitivity Analysis	H. Schulz & J. Sievers
• Crack Arrest	R .Gillot & C. Wiesner
• Residual Stresses	E. Keim
• Probabilistic Approach	J. Wintle
• Consistency in Fracture Assessment Criteria	R. Rintamaa, K. Wallin & U. Ehrnsten
• Relevance for Reactor Transients	C. Faidy
• Codes and Standards	P. Mignot
• Relation to other Large Scale Projects	R. Bass, S. Crutzen & R. Murgatroyd
• Technology Transfer to other Nuclear and Non Nuclear Plant	F.Boydon
• Lessons from Networking	F. Boydon

Summary Reports

• Final NESC Overview Report	R. Bass, J. Wintle & R. Hurst

These reports are available to NESC network members from the NESC operating agent: European Commission Joint Research Centre, Petten, The Netherlands.

Acknowledgements

This report presents the *Inspection Task Group Final Report* on the work conducted in the NESC-I Spinning Cylinder project. It has been edited by Mr. B. Murgatroyd (Inspection Reliability Consultancy) together with B. Eriksen, B. Houghton and P. Lemaitre (EC DG-JRC). Their expertise and dedication in compiling the present document is gratefully acknowledged.

As with all the NESC reports, this document represents a synthesis of a collective effort of experts from different organisations from Europe, as well as the USA. The full list of those who contributed to the NESC-I Project is shown below:

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D.P.G. Lidbury, AEA Technology plc; Mr. V.N. Lovchev, Kola NPP; Mr. T. Marshall, Rolls Royce Ltd.; Dr. B. Marini, CEA;
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Nicholson, HSE Health & Safety Executive (NII); Dr. P. Nurkkala, IVO Technology Centre Power Plant Technologies; Dr.
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Laboratory; Mr. J.B. Wintle, The Welding Institute; Mr. G.S. Woodcock, British Energy plc; Mr. K. Xanthopoulos, Swedish
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The Network for Evaluating Structural Components

Safe and efficient operation of nuclear power plant can be enhanced through better integration of the key structural integrity assessment technologies. To meet this challenge, the Network for Evaluation of Structural Components (NESC) was launched in 1992. Its objectives are:

- to create an international network to undertake collaborative projects capable of validating the entire structural integrity process.
- to work towards best practice and the harmonisation of international standards.
- to improve codes and standards for structural integrity assessment and to transfer the technology to industrial applications.

A 90-member network has been established. Operators, manufacturers, regulators, service companies and R&D organisations collaborate to perform large-scale experimental projects capable of serving as international benchmarks. The European Commission's Joint Research Centre acts as independent operating agent. The projects are designed to combine all aspects of structural integrity assessment including inspection, materials characterisation, fracture mechanics and instrumentation.

- NESC-I looks at the exploitation of the integrated approach to provide a robust safety case for pressurised thermal shock (PTS) of an aged, defect containing, reactor pressure vessel. It is unique insofar as the inspection and fracture mechanics analyses have been carried out without exact knowledge of the defects, as is the case for operational plant. The test was performed in March 1997 and the evaluation of the results was completed in 2000.
- NESC-II also features the PTS problem, but with the focus on the brittle fracture behaviour of shallow, sub-clad defects. Two large-scale experiments were conducted in 1999 at MPA Stuttgart. The results are presently being analysed.
- NESC-III will be launched in autumn 2000 and will focus on applying the integrated approach to structural integrity assessment of dissimilar metal welds in pipe sections.

EXECUTIVE SUMMARY

The Network for Evaluating Structural Components (NESC) was initiated to provide a network that would enable international collaboration on an investigation of the reliability of factors and procedures that are central to the evaluation of the structural integrity of pressurised components. The first project in the Network, NESC 1, utilised the spinning cylinder facility at AEA Technology, Risley to investigate the fracture behaviour of nuclear reactor pressure vessels under conditions of pressurised thermal shock.

From an inspection point of view, major objectives were to determine the effectiveness of typical in-service inspection procedures and to examine the interaction of the inspection results with the structural integrity assessment codes used to predict the growth behaviour of defects in the test cylinder. For the integrated evaluation of the integrity of the cylinder to be successful a knowledge of the mechanical and fracture properties of the specific steel used in the project was essential, thus three major disciplines were involved interactively in the project.

Technical responsibility for the activities falling within these disciplines was held by three Task Groups covering, respectively, inspection, material properties and fracture mechanics, and a fourth dealt with the instrumentation of the cylinder during the spin-test. A fifth Task Group co-ordinated the interaction between the other four on inter-group matters.

The objectives of the Inspection Task Group (TG1) were:

- To evaluate the effectiveness of current ISI procedures.
- To investigate how the inspection data are interpreted by structural analysis methods.
- To contribute to an evaluation of the conservatism of the entire structural integrity analysis process.
- To provide information on best practices.
- To transfer technology to industry.
- To give guidance on improving relevant codes and standards, and harmonising international standards.

To ensure that the inspection objectives were achieved six Evaluation Tasks were specified by TG1. These were:

1) To analyse the detection and sizing performances of the inspection teams and determine the accuracy of the inspection data.
2) To determine as far as possible, the factors influencing inspection performance.
3) To assess the impact of human error.

4) To make a recommendation on best practice for ISI.

5) To comment on the suitability of the defects used in the NESC inspections for wider use in ISI qualification.

6) To produce a TG1 final report.

It was specified at the outset of the project that the identity of the inspection teams participating in the inspection round robin exercise would be maintained absolutely confidential, and so a Referee Group was set up within JRC Petten with the sole responsibility of interacting with the inspection teams to observe the on-site inspections, receive and verify the results, and analyse the inspection data reported by the teams. A Data Analysis Group (DAG) was instituted as a sub-group of the Inspection Task Group 1 consisting mainly of technical experts from the teams with the prime responsibility for specifying the rules and guidelines for analysing the inspection data, and for discussing and approving the results emerging from the analysis performed by the Referee Group.

Prior to the commencement of the inspections the inspection teams were provided with sufficient information on the NESC cylinder to enable the teams to plan their inspections, but this information did not breach confidentiality concerning the defect parameters. Also, guidelines were issued for reporting the inspection data to the Referee Group, with the aim of allowing the importance and influence on performance of key inspection parameters to be assessed upon completion of the exercise. To obtain additional information on the inspection procedures a member of the Referee Group made at least one visit to each team during its inspection.

The inspection of the cylinder was carried out in two phases, the first was before the spin test on the cylinder and the second was after it. The first phase began in December 1995 and was completed in July 1996. After a successful spin test on the cylinder at AEA Technology on 20 March 1997 the cylinder was re-circulated to the inspection teams for the post-test inspections, which began in May 1997 and was completed in December 1997. Seven teams from Finland, France, Germany, Sweden, UK, USA and Russia participated in the pre-spin inspections using ultrasonic techniques, and these together with three additional teams from Germany took part in the post-spin inspection phase, together with two teams that used eddy current techniques. An eleventh team provided an analysis of the German post-test inspection data.

In order to keep the identity of the teams absolutely confidential the Referee Group developed a letter code which enabled the results to be analysed and presented in a way that did not breach confidential. For much of the analysis of the data the BTB Code, developed for the PISC exercise, was used.

The inspection results supplied by the teams were transferred into the BTB code database, which was then circulated to the teams for confirmation that it correctly represented their results. Any minor changes requested were allowed and were duly noted by the Referee Group, however, teams were not allowed to change their report on defects detected. Other changes were made by the Referee Group to ensure that the data conformed to the rules of the TG1 DAG, and these were also recorded. All changes made were examined to determine as far as possible the reason or cause.

The parameters used to determine the performances of the inspection teams were: detection rate; false call rate; accuracy of sizing the through-wall extent (TWE) and length of the defects; and the capability to profile the contours of the larger defects.

SUMMARY OF RESULTS

Detection performance was generally good with all the defects being detected by five of the seven teams in the pre-test inspections and eight out of ten in the post-test inspections. One of the two teams not achieving 100% detection was the same in both phases. The other teams missing defects were different in the two phases of the inspections. One of these teams, using manual techniques, missed a group of four underclad cracks pre-test, but detected them post-test. Training in the intervening period and an addition to the manual team for the post test inspection may have contributed to the improvement in the detection performance of this team. The second team, using automated scanning, reported a group of underclad cracks in the first inspection but missed them in the second. Since the same staff, equipment and procedures were used in both phases of the inspections this suggests that a human error was made in either setting up the equipment, scanning or interpreting the signals obtained.

The ultrasonic techniques used for detection ranged from: pulse echo using single crystal and twin crystal probes in either shear wave mode or longitudinal mode; focussed probes; phased arrays; tandem; SAFT and TOFD. The detection threshold varied from noise level to a 20 mm^2 FBH. When the results are examined in terms of the techniques employed by all the teams there is no evidence that the detection procedure or techniques used exerted a significant influence on detection capability. Indeed, the observation that non-detections occurring in the first phase were rectified in the second by one team, and conversely that another team missed defects in the second phase that it had found in the first indicates that the techniques employed were inherently capable of detecting the defects and that the failure to do so was due to some other cause, possibly human error in setting up the equipment, scanning or interpreting the data obtained.

The detection performance of the two teams using eddy current techniques was not as good as for teams using ultrasonic techniques, one detecting only 6 out of 15 defects and the other 11 out of 15. It must be recognised that the defects in the NESC 1 cylinder were not entirely suitable for eddy current techniques. This is discussed in detail in 9.1.
The ultrasonic inspection teams made no false calls in the pre-test inspections and in the post-test inspections only 1 of the 10 teams made any false calls. Each of the eddy current teams made some false calls in the post-test inspections. However, it must be recognised that the Eddy Current techniques are capable of picking up micro-structural changes in the materials.

Through wall extent sizing accuracy was good for the majority of the teams.

In the pre-test inspections the accuracy of 4 of the 7 teams in sizing the through-wall extent of the defects was very good with a mean error of 2 mm or less and a standard deviation for four of them of less than ±3 mm. The corresponding RMS error for these 4 teams was 3.4 mm or less. The fifth team had also had a good mean error result of 0.1 mm, but a standard deviation of ±7.6 mm. The two remaining teams however showed significant undersizing of most of the defects in their pre-test inspections, including in particular the large sub-clad fatigue crack.

In the post-test inspections, 4 teams sized the through-wall extent of the defects very accurately with a mean error of less than 1 mm and a standard deviation of ±2.5 mm or less. The corresponding RMS error for these 4 teams was 2.4 mm or less. Five other teams achieved a similar mean error with a standard deviation of better than 6.8 mm. The remaining team, as in their pre-test inspection, showed significant undersizing and a large standard deviation.

The individual through wall extent sizing results for each team are shown in appendices 5 and 7 for the pre-test and post-test inspections, respectively. Two of the good teams, CC and KK, achieved sizing accuracies of the defects in both inspections that could hardly be bettered, as did team EE in the post-test inspection.

The 4 teams, which performed best in TWE sizing, with an RMS error of 2.4 mm or less, all utilised the tip-diffracted wave from the crack tip to size the defects, however they used different techniques to obtain the crack tip signal. The techniques used are listed below.

1) TOFD
2) Crack Tip (PE SAFT)
3) Crack Tip (PE Focus)
4) Crack Tip (Conventional PE)

This result is very important in that it indicates that for good sizing of the through-wall extent of defects it is necessary to base the sizing technique on the tip-diffracted wave from the defect. On the basis of the evidence obtained in the present studies it appears that the specific technique used to obtain the crack tip signal is not influential.

The length sizing accuracy was good for some teams others made significant oversizing errors.

The accuracy of measurement of growth of the large underclad defect varied. Of the six teams who submitted relevant data, two were very accurate, with measurements within 0.5 mm of the actual growth of 5 mm. One team reported a small decrease of 1 mm and one team reported a small increase of 1.5 mm. The last two teams made significant errors in the crack growth prediction.

The results indicate that very good sizing accuracy of the through-wall extent of the defects was achieved using the diffracted signal from the crack tip. Since most of the teams used techniques based on obtaining the tip-diffracted wave, the variability in sizing accuracy appears to stem, to some extent, from the inspection system, procedure, or the personnel of the inspectors rather than the technique itself.

As part of the reporting procedure teams were asked to determine, if possible, the profile of the large defects, although this request was not mandatory. Destructive examination of the cylinder after the final inspections showed clearly that during the spin test both of the large defects grew, mainly in an axial direction just below the cladding/base metal interface, giving lobes at both ends of the sub-clad fatigue crack (defect B) and one lobe at the end of the through-clad crack (defect RL). Five teams provided profiles of the large sub-clad fatigue crack (B) at the pre-test inspection stage and eight gave profiles of both the large defects at the post-test stage which in general were good and conformed to the profile of the cracks in the deeper regions. However, the profiling of one team in the post-test inspections was outstanding and using focussed probes, accurately followed the contours of the lobes on the two cracks.

The conditions applicable to the NESC inspections were more favourable than those encountered on-site. The inspections were carried out in laboratory-type conditions with ready access to both the inside and outside surfaces of the cylinder, this is not the case for some nuclear pressure vessels although for others it is and such inspections are made. Examination of the data obtained in these studies indicates that the detection or sizing capability was not influenced by the side from which the inspection was performed (inside, outside or a combination). However, this observation is influenced by the smooth surface condition of the cladding.

Another possible influential factor was the number of techniques used by a team, since a larger number of probes, in principle, give more chances of obtaining a signal. However, examination of the results indicates that there is no significant difference in performance between teams using one or two techniques and those using five to seven. Also, a smaller scanning raster was employed in the present studies for the detection stage than would generally be expected in an on-site inspection, however from the limited data available this does not appear to have been a significant detection factor. For sizing, it is common practice for inspectors to use small raster scans, so the sizing procedures used in the present tests conform, in general, to the procedure used in practice.

It is considered that the smooth-machined surface finish and relatively small thickness of the cladding (4 mm) probably contributed to some extent to the good results achieved in the inspections, since other studies have shown that considerable variability in beam amplitude and direction can result from inspecting through an as-clad surface finish.

From the results it is considered that four key elements contributed to the good inspection performance observed in the NESC inspection exercise.

- The use of high detection sensitivity
- The use of crack tip diffraction techniques for sizing the through-wall extent of the defects

- The application of well-based inspection procedures by knowledgeable operators
- Good inspection conditions for the NESC 1 exercise

The main reasons why some teams did less well are considered to be due to:

- The occurrence of human error, which probably accounted for the non-detection of some of the smaller defects and the undersizing of the larger fatigue cracks.
- The limited inherent capability of the specific techniques employed, which are illustrated by:
    - the results achieved in sizing the through-wall extent ultrasonically using amplitude based methods
    - the oversizing of defect length by one team using full skip sound path

These results show the importance of verifying the capability of an entire inspection system, including the inspection procedures and personnel, using inspection qualification methodologies relevant to the specific inspection application.

With respect to the type of defect used in the exercise and their suitability for general use in inspection qualification test assemblies, the results indicated that the sub-clad EDM notches with sharp tips appeared to be at least as difficult to size as the realistic sub-clad defects (hot and cold cracking). This makes them suitable for use in qualification testing, but care is needed to avoid the occurrence of porosities in the cladding both over and near the defect during the cladding process. This shows that destructive analysis upon completion of the qualification exercise may be essential to fully certify the defects and their parameters.

CONCLUSIONS:

The following general conclusions can be drawn from the results of the inspection programme.

1. The prime objective of this international round robin inspection exercise to gather inspection information on the detection and sizing capability of a range of inspection techniques was successfully achieved.

2. The objectives of identifying some of the factors influencing the quality of inspection performance and indicating how procedures may be optimised have been achieved.

3. The accuracy of defect sizing achieved by the majority of the inspection teams enabled correct predictions of the growth behaviour of the defects in the cylinder during the spin-test to be made by the NESC Structural Integrity Group, TG3.

4. The detection performance achieved with ultrasonic techniques was good. Furthermore, the ultrasonic teams made no false calls in the pre-test inspections, and only one team made false calls in the post-test phase. This is the ideal performance from a reliability and cost-effectiveness point of view

5. The detection results achieved with eddy current techniques were below the performances of the ultrasonic techniques. However, it must be recognised that the defects in the NESC 1 project were not entirely suitable for Eddy Current techniques. Furthermore, both the eddy current teams made some false calls, which possible could be explained by the fact that the Eddy Current techniques are capable of picking up small micro-structural changes in the materials.

6. Sizing of the through-wall extent and length of the defects was very good for the majority of the teams using several different techniques. It is considered that this was due firstly to the selection of optimum techniques for the purpose, secondly to the ability of the inspectors, and thirdly to the ability to control the occurrence of human error.

7. For sizing through-wall extent, techniques using the tip-diffracted wave of the defects were particularly effective, whilst for length sizing, amplitude drop methods were effective.

8. Most teams showed an ability to profile the deeper contours of the two large fatigue cracks; however, one team using focussed probes was capable of contouring the profile of the lobes at the ends of the defects.

9. The different number of techniques used by the different inspection teams was not found to be significant in defining inspection performance, and on limited information, it appears that scanning raster did not significantly influence detection performance.

10. In the study, the sharp-tipped, sub-clad EDM notches were found to be more difficult to detect than realistic hot or cold cracking. This indicates that EDM notches could be considered when designing test assemblies for inspection qualification testing.

11. The presence of porosities in the cladding above the EDM notches and the cold and hot cracking, most probably caused by the fabrication method, is something to be avoided. The presence of such porosities indicates the need to verify the defect fabrication methods used.

12. In general, the detection performances achieved in NESC 1 were better than the results obtained in PISC II, indicating that lessons have been learned from previous international exercises.

13. The studies show that human error must be controlled. This aim will be assisted by well-written unambiguous procedures both for data acquisition and data analysis, good quality control, training (including on-the-job training) and qualification of the inspection team. In addition, in-service inspection conditions should also be considered. Inspector motivation and the onset of tiredness are factors that can influence the effectiveness of inspectors, and the influence of other factors, such as long working hours, shift work, pressure of management, radioactive conditions, and tedium should all be considered when planning an in-service inspection.

14. The results indicate the importance of, and the need for, inspection qualification to verify and confirm that the entire inspection system, including the inspection procedure and personnel, is capable of meeting the inspection objectives defined at the outset. The results obtained also show the need to separate the procedure qualification from the personnel qualification, in order to identify exactly where the problems are, if something should go wrong.

RECOMMENDATIONS:

From the results and conclusions of the work performed in the NESC 1 project by the Inspection Task Group the following recommendations are made with the purpose of ensuring, as far as is possible, firstly, that the capability of the entire inspection system, including equipment, inspection procedures and personnel, is adequate for the intended purpose, and secondly, that high reliability is achieved when the inspection is performed on-site,

1. For accurate sizing of the through-wall extent of a defect it is recommended that a sizing technique based on the use of the tip-diffracted wave from the defect is employed. However, since inspection teams using this technique did not perform equally well in the NESC 1 study, it is recommended that the inspection system, and personnel, should be qualified on appropriate test specimens and defects.

2. It is recommended that precautions should be taken to reduce the incidence of human error as far as possible. This aim will be assisted by well-written unambiguous procedures both for data acquisition and data analysis, good quality control, training (including on-the-job training) of the inspection personnel. In addition it is recommended that the influence of in-service inspection conditions on the performance of the inspectors should be considered. Some of the factors that should be included in assessment are:
    - inspector motivation and tiredness
    - long working hours
    - shift work
    - pressure of management
    - radioactive conditions
    - tedium

3. It is recommended that when selecting techniques for practical ISI applications, the condition of the cladding should be taken into account when specifying the parameters of the ultrasonic transducers. With optimum probe parameters it should be possible to reduce significantly the influence of cladding on inspection reliability. It is also recommended that the effectiveness of inspection procedures for a specific inspection involving cladding should be verified by inspection qualification methodologies using test specimens with relevant cladding.

4. It is recommended that the fabrication methods used to insert defects in test specimens should be verified to avoid, as far as possible, the inclusion of unintended reflectors in the vicinity of the intended defect.

5. It is recommended that the entire inspection system, including the equipment, inspection procedure and personnel, should verified by inspection qualification methodologies prior to an on-site inspection to

   demonstrate that it is capable of meeting the specified inspection objectives. However, in cases where equipment and procedure are accepted by appropriate safety authorities, it may only be necessary for the inspectors to pass suitable personnel qualification examinations.

6. In view of the observation that many of the teams used similar detection and sizing techniques yet obtained different results it is recommended that, following completion of the NESC 1 project, a further analysis of the NESC 1 data be made to investigate the influence of factors such as the quality of: the inspectors; the scanner and equipment; and the data processing equipment and software, on performance. In addition, such studies would analyse the procedures used by the teams that performed particularly well in order to obtain a better understanding of the techniques that could be used to achieve good results. Such studies would require the co-operation of the teams involved, but would be carried out without breaching the confidentiality observed in the round robin trials.

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1 INTRODUCTION

The Network for Evaluating Structural Components (NESC) was initiated to provide a network that would enable international collaboration on an investigation of the reliability of factors and procedures that are central to the evaluation of the structural integrity of pressurised components. The founding sponsors were the UK Health and Safety Executive (HSE) and the Joint Research Centre (JRC-Petten site) of the EC, and the Network was launched at the HSE's Laboratories in Sheffield in 1993[1].

The first project in the Network, NESC 1, utilised the spinning cylinder facility at AEA Technology, Risley to investigate the fracture behaviour of nuclear reactor pressure vessels under conditions of pressurised thermal shock. The spinning cylinder test was carried out on 20th of March 1997 and was successful to the extent that crack growth occurred which was confirmed later by destructive examination.

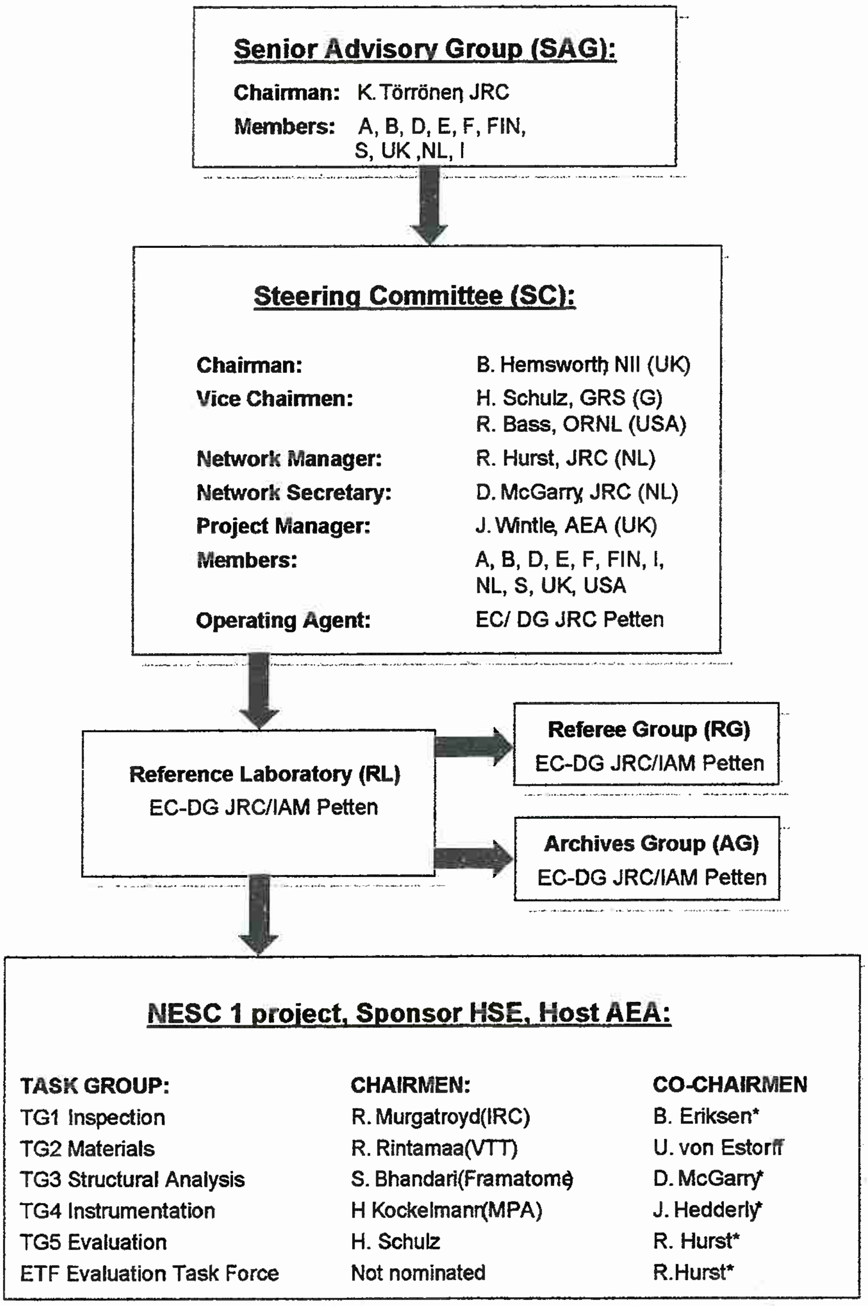
From an inspection point of view, the major objectives were to determine the effectiveness of typical in-service inspection procedures and to examine the interaction of the inspection results with the structural integrity assessment codes used to predict the growth behaviour of defects in the test cylinder. For the integrated evaluation of the integrity of the cylinder to be successful a knowledge of the mechanical and fracture properties of the specific steel used in the project was essential, thus three major disciplines were involved interactively in the project. A fourth task group was set up to instrument and measure the crack growth during the spinning of the NESC 1 cylinder.

The organisations participating in NESC 1 represented Austria, Belgium, Finland, France Germany, Italy, Netherlands, Spain, Sweden, Switzerland and the UK in Europe, and also organisations in Japan and the United States participated. A team from Russia participated in the inspection round robin. Each member was a signatory to the formal multi-partner collaboration agreement and provided substantial support to all aspects of the project.

This report summarises the results, conclusions and recommendations of the Inspection Task Group (TG1).

2 MANAGEMENT STRUCTURE

The management structure of NESC 1 is outlined in Figure 1.



TASK GROUP:	CHAIRMEN:	CO-CHAIRMEN
TG1 Inspection	R. Murgatroyd(IRC)	B. Eriksen*
TG2 Materials	R. Rintamaa(VTT)	U. von Estorff
TG3 Structural Analysis	S. Bhandari(Framatome)	D. McGarry*
TG4 Instrumentation	H Kockelmann(MPA)	J. Hedderly*
TG5 Evaluation	H. Schulz	R. Hurst*
ETF Evaluation Task Force	Not nominated	R.Hurst*

* **All NESC 1 Co-chairmen:** EC-DG JRC/IAM Petten

Figure 1 Management structure of the NESC 1 Project.

The executive body is the Steering Committee, composed of members from the participating organisations. The Operating Agent was the JRC, Institute for Advanced Materials at Petten, which had responsibility for operating the Network and acting as a neutral arbitrator. Technical responsibility for the activities falling within the disciplines of, respectively, inspection, material properties, fracture mechanics and test instrumentation was held by four Task Groups (TG1 to 4) with a fifth Task Group (TG5) co-ordinating the interaction between the other four. Towards the end of NESC 1 the role of TG5 was broadened to include responsibility for administering tasks which extended across the Task Groups and were therefore of a multi-disciplinary nature, consequently TG5 was renamed the Evaluation Task Force (ETF) and its membership was changed accordingly. All the Task Groups reported to the Steering Committee.

Terms of Reference were defined for TG1, and as part of these it was specified at the outset of the project that the identity of the inspection teams participating in the inspection round robin exercise would be maintained absolutely confidential. To observe this condition a Referee Group was set up consisting of a very small number of staff from JRC-Petten which had sole responsibility of interacting with the teams to observe inspections, receive and verify results and analysis the inspection data reported by the inspection teams.

A Data Analysis Group (TG1-DAG) was instituted as a sub-group of Task Group 1, which consisted mainly of technical experts from the teams with the prime responsibility for specifying the rules and guidelines for analysing the inspection data. Furthermore the group should review and approve the results emerging from the analysis performed by the Referee Group.

3 THE OBJECTIVES

3.1 Objectives of the NESC 1 Project

The objectives of NESC 1 specified at the outset of the project were:

- To evaluate the effectiveness of current ISI procedures.
- To investigate how the inspection data are interpreted by structural analysis methods.
- To compare the predictions of structural analysis codes.
- To predict the behaviour of underclad and through-clad cracks when subjected to pressurised thermal shock.
- To evaluate the conservatism of the entire structural integrity analysis process.
- To provide information on best practices.
- To transfer technology to industry.
- To give guidance on improving relevant codes and standards, and harmonising international standards.

3.2 Objectives of the Inspection Task Group

One of the principle objectives of the Inspection Task Group (TG1) was to evaluate the effectiveness of current ISI techniques for a range of defect sizes. In addition, TG1 was also required to supply inspection data to TG3 for use in the structural integrity analysis codes being evaluated by that group. From the interaction between the task groups, the sensitivity of the predictions of crack stability determined by the analysis codes to variability in the accuracy of the inspection data could be examined. This sensitivity analysis was performed as an inter-task group Project Evaluation Task (PET) and the results are reported fully elsewhere in the NESC project[2]; a summary of the results are given in this report in section 16.6.

Six Evaluation Tasks (ET) were specified by TG1 to ensure that the inspection objectives were achieved. These were:

ET 1: To analyse the detection and sizing performances of the inspection teams and determine the accuracy of the inspection data.

ET 2: To determine as far as possible, the factors influencing inspection performance.

ET 3: To assess the impact of human error.

ET 4: To make a recommendation on best practice for ISI.

ET 5: To comment on the suitability of the defects used in the NESC inspections for wider use in ISI qualification.

ET 6: To produce a TG1 final report.

This report describes the information derived from the evaluation tasks and the results, conclusions and recommendations of the Inspection Task Group.

4 OUTLINE OF THE NESC 1 PROGRAMME

The spinning cylinder rig used in the NESC 1 programme is a facility for investigating the fracture behaviour of thick section steel specimens under combined mechanical and thermal stresses. The design concept is that rotating a cylinder at high speed at a selected temperature simulates the stress distribution in a reactor pressure vessel. When the predetermined test conditions are achieved then secondary stresses are imposed representatives of Pressurised Thermal Shock (PTS) conditions by cooling the inner surface with a spray of cold water. A detailed description of the spinning cylinder concept and test facility together with the specific conditions employed in the NESC 1 test are described in "NESC project final report - A description of work carried out up to and including the spinning cylinder test"[3]. The range of defects inserted in the NESC cylinder prior to the spin test is detailed in Section 5 of this report. In outline, the main phases of the NESC 1 programme were:

- To procure a cylinder fabricated from a steel with degraded properties typical of a reactor pressure vessel aged by irradiation
- To determine the relevant mechanical properties of the steel
- To introduce carefully selected sub-clad defects into the inner regions of the cylinder covering a range of sizes, some of which would grow during the thermal quench of the cylinder
- To deposit two layers of strip cladding on the internal surface of the cylinder using a commercial procedure
- To introduce an additional defect through the cladding
- To machine the cladding to the final 4 mm thickness
- To arrange for the participating inspection teams to inspect the cylinder prior to the spin test
- To use the inspection results in structural integrity assessment to evaluate the growth behaviour of the defects during the spin test of the cylinder
- To subject the cylinder to the spin test
- To re-inspect the cylinder after the spin test
- To determine the true size of the defects by detailed destructive examination of the cylinder
- To analyse and report the results of the inspection, fracture mechanics and mechanical properties studies
- To disseminate the information derived by the project to appropriate bodies and organisations

The cylinder was given appropriate heat treatments during the fabrication stage and details of these are given in the NESC 1 final report[4].

5 DESCRIPTION OF THE TEST PIECE AND DEFECTS INTRODUCED

5.1 Fabrication of the Cylinder and Defects

A detailed description of the fabrication programme for the cylinder is given in the NESC 1 final report[5]. Briefly, the NESC 1 cylinder was fabricated from two halves of cylinders used previously in the AEA Technology test programme[3]. These were welded together by MPA in Stuttgart, Germany with axial narrow gap submerged arc welds, and then a large fatigue crack (defect B) was introduced from the inner surface of the completed cylinder using pulsating oil pressure techniques[5]. The cylinder was machined to an internal diameter of 1052 mm and five defects were introduced at MPA using electro-discharge machining (EDM) techniques to give EDM notches with a sharp radius on the crack tips (defects A, G, K, L and Q). The cylinder was transferred to Framatome for cladding and the insertions of realistic underclad cracks using proprietary techniques. The cladding was 2-layer strip cladding with an average thickness of 10 - 11 mm. After the integrity of the cladding was verified by ultrasonic inspection a through-clad fatigue crack (defect H) was introduced at MPA by building up the cladding locally over an appropriately sized area and again applying the pulsating oil technique with a starter notch. During this process unplanned stresses occurred which caused some debonding of the cladding around the defect and branching of the crack. The morphology of this crack was determined by JRC, Petten with radiographic and ultrasonic techniques and a decision was taken by the NESC Steering Committee (SC) not to include this defect in the inspection trials; teams could however report their findings on this defect if they wished.

The cylinder was machined in the UK down to the specified final dimensions, which required that the cladding should be 4 mm thick. This thickness was necessary to obtain the desired crack initiation driving forces during the spin test of the cylinder to give crack growth at the large fatigue cracks. From an inspection point of view it is important to note that this cladding thickness is unusually small, also the cylinder possessed a smooth surface finish, and the influence of these factors on the inspection results obtained is discussed below.

While the cylinder was circulating to the participating laboratories for the first phase of pre-spin inspections the NESC SC decided to insert another through-clad defect in the cylinder as a replacement for the through-clad defect described above. So, after completion of the first phase of inspections an EDM notch (defect RL) was inserted at JRC, Ispra that had a sharp radius at the crack tip. The tip was further sharpened by fatigue at AEA Technology, Risley to give small crack extension of less than 2 mm at the deepest point, with crack extension occurring around the edge of the defect to the surface of the cylinder. Crack extension was greatest just below the interface between the cladding and the mild steel base metal, and this was measured during destructive examination to be in excess of 10 mm in this region.

The weight was approximately 6.8 tons and the final dimensions of the cylinder were measured accurately to be:

Outer diameter	1395 mm
Inner diameter	1045 mm
Wall thickness	175.5 mm
Cladding thickness	4.0 mm
Length	1296 mm

5.2 Co-ordinate system used for the reporting of the indications and defects

The co-ordinate system used for reporting of the ultrasonic data is given in Figure 2. The teams were requested to follow strictly this co-ordinate system for the reporting of indications.

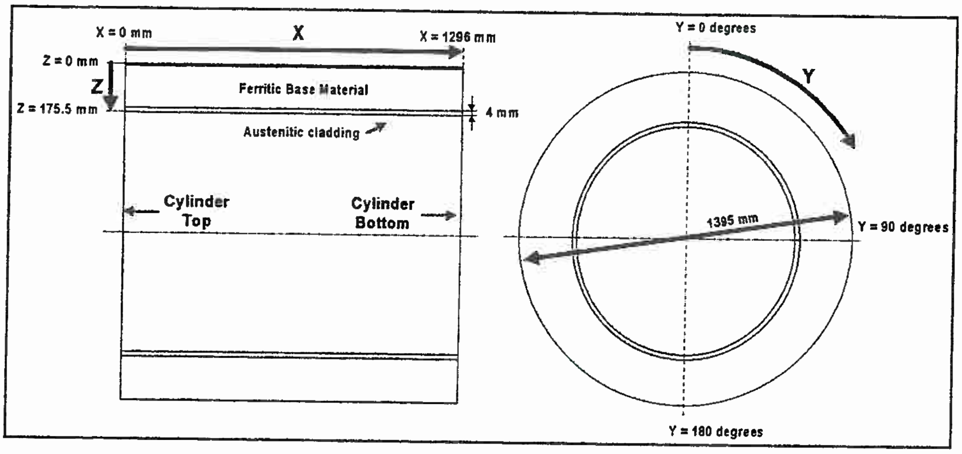


Figure 2 Dimensions of the NESC 1 cylinder and the co-ordinate system used for reporting of defects and indications

5.3 Defects inserted in the NESC 1 cylinder

Initially, a total of 17 defects were inserted intentionally into the cylinder before the first pre-test round robin trial. The inserted defects can be subdivided into the following three categories:

1) Large fatigue defects

The cylinder initially contained two defects of this type, one surface breaking (B) and one non-surface breaking (H) known as the complex defect. The latter was not included in analysis of the inspection results.

After the first inspection and before the PTS-test of the cylinder a third large defect (RL) was inserted into the cylinder. It was a large fatigue sharpened EDM notch and it therefore falls in the category of large fatigue defects.

2) Smooth planar EDM defects (PISC type A):

The cylinder contained five defects of this type with flaw heights ranging from 2.5 mm to 25.5 mm

3) Realistic underclad cracks:

Three groups of defects were inserted into the cylinder to simulate underclad cracking.

- two groups of 3 defects (hot cracking defects). Each of these groups contained an additional defect, but they were not considered as their principle plane lay in the circumferential direction.
- one group of 2 defect (cold cracking defects)

Of the 17 defects inserted before the pre-test RRT 3 is not considered for the evaluation in this report; defects F and P was two circumferential defects, defect H was the large fatigue defect with complex nature.

A number of areas of the NESC 1 cylinder were not considered for inspection, of which the inspection teams, were informed before the start of the round robin trials.

- the areas 150 mm from the top and bottom of the cylinder where no cladding was deposited.
- the welding area where the 2 half cylinders had been welded together to the NESC 1 cylinder.
- the areas of the thermocouple holes used during the PTS test of the cylinder.

The locations and sizes of the defects in the cylinder were determined in detail by careful Destructive Examination (DE) after the post-test inspections. This was carried out at Reference Laboratory (JRC, Petten) and took into account the results submitted by the inspection teams, so that reports of unintended indications could be assessed in order to provide information on false calls. As part of the DE many of the defects were cooled in liquid nitrogen and broken open to determine from the morphology of the crack faces what the original size had been prior to the spin test on the cylinder and whether there was evidence of crack growth due to the spin test.

The DE revealed that some of the EDM notches (G, L and Q) and all but one of the underclad cracks contained porosities in the cladding above these defects. The DE also showed that two of the implanted underclad cracks contained smaller cracks oriented perpendicular to the main crack (D and E).
For the assessment of the pre-test and post-test inspection results respectively 14 and 15 defects were considered. The pre-test co-ordinates and dimensions of the different defects are shown in Table 1.

ID	Defect type	X_1 [mm]	X_2 [mm]	Y_1 [°]	Y_2 [°]	Z_1 [mm]	Z_2 [mm]	Length □X [mm]	TWE □Z [mm]
Large Fatigue defect									
B	Underclad Fatigue Crack	482	743	37.8	38.3	95.0	171.5	261	76.5
Smooth planer EDM notches (PISC type A)									
A	Underclad EDM (low ratio)	959	978	28.2	28.3	166.0	171.5	19	5.5
G	Underclad EDM (low ratio) [1]	239	286	121.9	122.1	158.0	171.5	47	13.5
K	Underclad EDM (low ratio)	967	1036	217.8	218.3	147.0	171.5	69	24.5
L	Underclad EDM (high ratio) [1]	493	510	238.1	238.3	169.0	171.5	17	2.5
Q	Underclad EDM (high ratio) [1]	781	818	325.8	326.1	165.0	171.5	37	6.5
Implanted realistic defects ("Hot- and Cold Cracking")									
C	Underclad Hot Cracking [1]	277	307	68.4	68.9	166.0	171.5	30	5.5
D	Underclad Hot Cracking [2]	330	355	68.2	69.4	164.0	171.5	25	7.5
E	Underclad Hot Cracking [1], [2]	251	273	73.6	74.2	165.0	171.5	22	6.5
I	Underclad Cold Cracking [1]	575	630	204.7	205.5	150.0	171.5	55	21.5
J	Underclad Cold Cracking [1]	650	688	204.7	205.4	152.0	171.5	38	19.5
M	Underclad Hot Cracking [1]	620	645	297.2	297.6	168.0	171.5	25	3.5
N	Underclad Hot Cracking [1]	679	706	297.2	297.8	167.0	171.5	27	4.5
O	Underclad Hot Cracking [1]	577	602	303.0	303.4	166.0	171.5	25	5.5

[1] Small porosity was evident in the cladding near the defect

[2] Small perpendicular cracks was associated with the main crack

Table 1 Pre-test co-ordinates and dimensions of defects considered in the analysis

The locations of the intended defects used for the assessment of the inspection data are shown Figure 3.

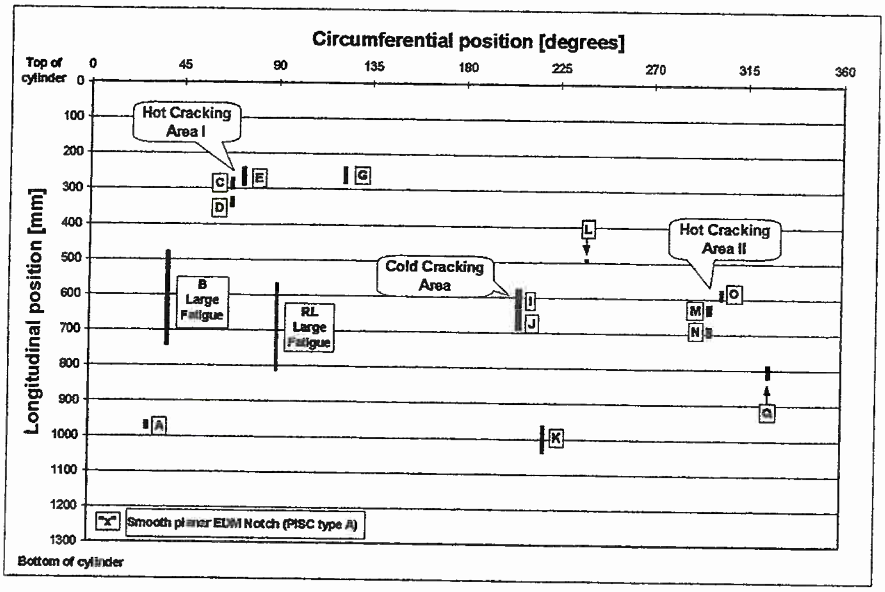


Figure 3 Overview of the location of the intended defects used for the analysis of the NESC 1 inspection data.

Table 2 shows the the post-test co-ordinates and dimensions of the defects. Three defects, RL, B and K had experienced growth and these final dimensions are recorded in Table 2.

ID	Defect type	X_1 [mm]	X_2 [mm]	Y_1 [°]	Y_2 [°]	Z_1 [mm]	Z_2 [mm]	Length □X [mm]	TWE □Z [mm]
Large Fatigue defect									
B	Underclad Fatigue Crack	477	753	37.8	38.3	90.0	171.5	276	81.5
RL	EDM + Fatigue Crack [3]	597	821	89.0	90.3	101.0	175.5	224	74.5
Smooth planer EDM notches (PISC type A)									
A	Underclad EDM (low ratio)	959	978	28.2	28.3	166.0	171.5	19	5.5
G	Underclad EDM (low ratio) [1]	239	286	121.9	122.1	158.0	171.5	47	13.5
K	Underclad EDM (low ratio)	967	1036	217.8	218.3	146.0	171.5	69	25.5
L	Underclad EDM (high ratio) [1]	493	510	238.1	238.3	169.0	171.5	17	2.5
Q	Underclad EDM (high ratio) [1]	781	818	325.8	326.1	165.0	171.5	37	6.5
Implanted realistic defects ("Hot- and Cold Cracking")									
C	Underclad Hot Cracking [1]	277	307	68.4	68.9	166.0	171.5	30	5.5
D	Underclad Hot Cracking [2]	330	355	68.2	69.4	164.0	171.5	25	7.5
E	Underclad Hot Cracking [1], [2]	251	273	73.6	74.2	165.0	171.5	22	6.5
I	Underclad Cold Cracking [1]	575	630	204.7	205.5	150.0	171.5	55	21.5
J	Underclad Cold Cracking [1]	650	688	204.7	205.4	152.0	171.5	38	19.5
M	Underclad Hot Cracking [1]	620	645	297.2	297.6	168.0	171.5	25	3.5
N	Underclad Hot Cracking [1]	679	706	297.2	297.8	167.0	171.5	27	4.5
O	Underclad Hot Cracking [1]	577	602	303.0	303.4	166.0	171.5	25	5.5

[1] Small porosity was evident in the cladding near the defect

[2] Small perpendicular cracks was associated with the main crack

[3] The RL defect not present during pre-test inspections

☐ Indicates no change from pre-test sizes

Table 2 Post-test co-ordinates and dimensions of defects considered in the analysis

The destructive examination revealed also the presence of 5 unintended defects. The co-ordinates and dimensions for these are shown in Table 3 together with the two intended circumferential defects and the complex fatigue defect H. Note that all these defects have not been considered for the assessment of the obtained inspection results.

Three of the unintended defects C', F', and P' were porosities in the base material. The 4th unintended defect J' was characterised as a cavity in the base material. The last unintended defect N' was a weld defect in the base material close to the second Hot Cracking area. All these defects are likely to originate from the manufacturing processes of the defects.

ID	Defect type	X_1 [mm]	X_2 [mm]	Y_1 [°]	Y_2 [°]	Z_1 [mm]	Z_2 [mm]	Length □X [mm]	TWE □Z [mm]
Large Fatigue defect (complex defect)									
H	Through clad fatigue crack	520	775	130.9	145.2	87.0	175.5	255	88.5
Implanted circumferential realistic defects ("Hot- and Cold Cracking")									
F	Underclad Hot Cracking [1], [2]	315	322	72.8	75.8	165.0	171.5	7	6.5
P	Underclad Hot Cracking	647	648	301.9	304.2	168.0	171.5	1	3.5
Unintended defects									
C'	Porosity	312	329	69.4	69.7	163.0	170.0	17	7.0
F'	Porosity	315	320	84.2	87.0	163.0	170.0	5	7.0
J'	Cavity	733	746	204.4	205.2	157.0	159.0	13	2.0
N'	Porosity and lack of fusion in box implant	765	774	292.7	294.3	160.0	162.0	9	2.0
P'	Porosity	645	648	301.1	301.3	162.0	167.0	3	5.0

[1] Small porosity was evident in the cladding near the defect

[2] Small perpendicular cracks was associated with the main crack

Table 3 Co-ordinates, dimensions and characterisation of defects not considered in the analysis.

Figure 4 shows graphically the position of the two intended circumferential defects (F and P), all the unintended defects (C', F', J' N' and P') and the complex defect (H). These defects were not taken into account in the assessment of length and TWE sizing carried out in this report. However, inspection teams, which had indications corresponding with these defects, were not penalised with false calls.

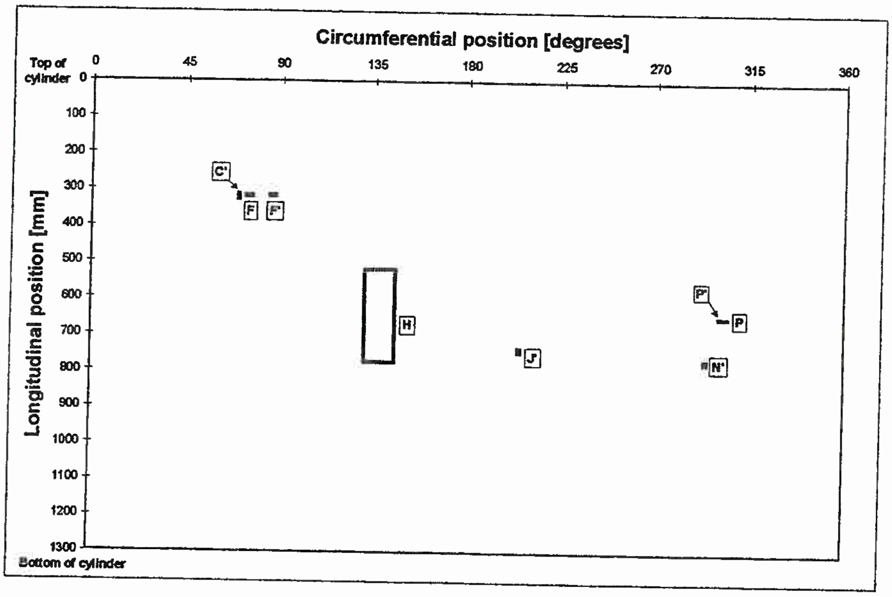


Figure 4 Graphical presentation of the position of the unintended defects and the two intended circumferential defects

6 MANAGEMENT OF THE INSPECTIONS

6.1 Data reporting requirements

Two documents were distributed prior to the start of the round robin trial to all participating inspection teams.

I. NESC TG1(95)3: Containing a technical specification of information relevant to the inspection of the NESC spinning cylinder specimen (see Appendix 1)

II. NESC TG1(95)4: Containing guidelines for the reporting of the inspection data for the NESC spinning cylinder (see Appendix 2)

The first provided information on the NESC cylinder (e.g. the size and weight of the cylinder) to enable the teams to plan their inspections,

It requested that the size and location of the large defects and the sharp EDM notches should be reported, and that if possible the profile of the two large defects should be reported; the latter was not mandatory but was desirable. For the realistic underclad defects, it requested that the size and location of the box enclosing the area of cracking be given, together with the size of the largest crack in the group. Appropriate calibration blocks were manufactured and provided by JRC, Petten for use by the teams, if required.

In detail it provided the following input information on the defects in the NESC 1 cylinder without violating confidentiality concerning defect size and location:

<u>Defect specification:</u>

1) Large fatigue cracks
2) Realistic underclad cracks
3) Artificial cracks

<u>Defect orientation:</u>

All defects within +/- 10 ° with respect to axial axis of the cylinder

<u>Reporting requirements:</u>

1) Large fatigue cracks:
    - location, maximum length and TWE
    - crack profile is optional, but highly desirable

2) Real underclad cracks:
- size and location of box enclosing cracked area
- TWE, length and position of largest cracks in the boxed area

3) Artificial underclad cracks (PISC type A):
- location, length and TWE

The second document contained the guidelines for reporting the inspection data to the Referee Group, and its purpose was to enable the importance and influence of key inspection parameters on inspection performance to be assessed upon completion of the exercise. The document was based on the guidelines developed for the PISC exercise and asked for detailed information to be provided on the equipment, techniques, procedures and personnel to be used for detection and sizing. The teams were also asked to give additional information about the decision process followed to analyse their inspection data. Furthermore, it asked for information on the training and qualification of the team members. Unfortunately, not all the teams provided the full record requested some giving only the integrated final results.

To provide additional information on the inspection procedures a member of the Referee Group made at least one visit to each team during its inspection.

6.2 Management of the Pre- and Post-test inspections

The inspection of the cylinder was carried out in two phases, the first was before the spinning test on the cylinder and the second was after it. The first phase began in December 1995 and was completed in July 1996. The second began in May 1997 and was completed in December 1997.

The circulation of the cylinder to the different participating inspection organisations was organised and managed by the JRC, Petten. Seven teams participated in the first phase using ultrasonic techniques, and these are identified in Table 4.

Company	Country	Comments
ABB-TRC	Sweden	
Battelle/NRC	USA	Inspection performed at JRC-Petten (The Netherlands)
CEA	France	
Kola NPP	Russia	Inspection performed at VTT (Finland)
RRA	United Kingdom	
Siemens KWU	Germany	
VTT	Finland	

Table 4 Teams participating in the pre-test inspection of the NESC 1 RRT.

Under the rules of the round robin inspections each team had two weeks to complete its inspection and one month to report its data, although in some cases the latter time-scale was relaxed slightly.

After the successful spinning of the cylinder at AEA Technology on 20 March 1997 the cylinder was re-circulated to the inspection teams for the post-test inspections. Four new teams opted to participate in the post-test inspections, of whom one only did through-wall extent analysis on data already recorded by another team. Another team changed their subcontracted vendor in the post-test inspection. The list of teams taking part in the second phase is given in Table 5.

Team	Country	Comments
ABB-TRC	Sweden	
ABB-ZAQ	Germany	New team participating in the post-test inspection
AEA Sonomatic	United Kingdom	New subcontactor participating in the post-test inspection
Alstom Energie	Germany	New team participating in the post-test inspection
BAM	Germany	New team participating in the post-test inspection
Battelle	USA	Inspection performed at JRC-Petten (The Netherlands)
CEA	France	
IZfP	Germany	New team participating in the post-test inspection
Kola NPP	Russia	Inspection performed at VTT (Finland)
Siemens KWU	Germany	
VTT	Finland	

Table 5 Teams participating in the post-test inspection of the NESC 1 RRT.

7 DATA ANALYSIS METHODOLOGY

7.1 Construction of the Data Base

One of the key issues defining both the inspections and the data analysis was that the identity of the teams taking part in the exercise should remain absolutely confidential. Therefore, in analysing the inspection results the Referee Group developed a letter code, which enabled the results to be discussed and presented in a way that did not breach confidentiality.

The BTB Code was used for much of the analysis of the data. The initials of the code denote different states of data retention, i.e., the first B stands for "Boat" and in general this state refers to the as-received data. Analysis of such data requires rules defining important aspects of the analysis; the rules for NESC 1 are described below. When the rules have been applied to the as-received data it becomes part of the "Train" referred to as "T", and this stage enables the inspection results to be compared with the reference information in both tabular and graphic form. Finally, the code enables the data to be analysed as a function of the techniques employed, provided that the teams have supplied such information, and this stage is defined as "Bus" in the Code and denoted by "B".

The figures corresponding with the "Boat" and "Train" of all individual teams are given in Appendices 3 and 4 respectively. The top figure on the BTB-plots corresponds with a projected C-scan (Top-view) whereas the bottom of the figure corresponds with a projected B-scan (Side-view). In these figures one finds boxes with different colours. The boxes in red correspond with the reference defects, the ones in green indicate the boxes reported by the teams, which correspond with a reference, and the boxes in blue correspond with false calls.

The indications corresponding with the residual stress holes have already been removed in the "Boat". The difference between the "Boat" and "Train" thus relate especially to the following aspects:

- Removal of circumferential indications
- Removal of indications corresponding with unintended defects

The inspection results supplied by the teams were first transferred into the BTB code data base and this data base was circulated to the teams for confirmation that it correctly represented their results. Any minor changes requested, such as typographical errors, were allowed and were noted by the Referee Group, however, teams were not allowed to change their report on defects detected. Other changes might be made by the Referee Group to ensure that the data conformed to the rules of the TG1 DAG, and these were also recorded in the database. All changes made were examined to determine as far as possible the reason or cause for the change, and the results of this evaluation together with all the changes to the data is presented in Section 8.

7.2 Performance parameters used in the analysis

The factors used to determine the performances of the inspection teams are based on those developed for the PISC exercise. They are defined as follows:

Detection Rate

FDF	Flaw Detection Frequency is defined as the number of defects detected by a team divided by the total number of defects in the volume inspected.
FDP	The Flaw Detection Probability is defined as the ratio of the number of teams, which have detected a specific defect with respect to the total number of teams that have inspected the areas where this defect was located.

False Call Rate

FCRD	The False Call Rate in Detection is defined as the number of false calls divided by the total number of indications reported by the team.

Through-wall Extent Sizing

Several parameters were used to assess the accuracy of sizing the through-wall extent of a defect (direction Z in the cylinder). These were:

MESZ	Mean error made by a team for all defects in TWE sizing
SESZ	Standard deviation associated with the mean error
MOS	Maximum OverSizing
MUS	Maximum UnderSizing
RMS-error	Root Mean Square error, which is defined as follows:

$$\text{RMS error} = \sqrt{\frac{\sum (u_i - v_i)^2}{n}}$$

with u_i : reference defect TWE
v_i : measured flaw TWE
n : number of measurements

Length Sizing

The parameters used to evaluate the accuracy of length sizing are the same as for sizing through-wall extent.

Capability to profile the 2 large fatigue cracks

This was a qualitative comparison of the reported profile with that determined by DE, with attention being paid to the fidelity of tracing the side lobes that occurred at the ends of the fatigue cracks during the spin test on the cylinder.

In interpreting these errors it is to be remembered that the mean error indicates the value of any systematic error that exists and will identify general under- or oversizing. However, a small mean error does not necessarily imply that sizing performance is accurate; measures of sizing accuracy are the standard deviation and the RMS error, which indicate the size of random error.

7.3 Rules specified for the data analysis

The TG1-DAG (Data Analysis Group) agreed the following rules for the data analysis.

1) The tolerance used for detection was 25 mm. This parameter specifies the maximum permissible separation between the 3-dimensional box defining the reference defect and that reported by an inspection team for a defect to be classified as detected. Figure 5 shows how the tolerance influences the post-test detection of defects C, K and I. It is clear that the values for detection probability remain almost unchanged for values of the tolerance larger than 25 mm.

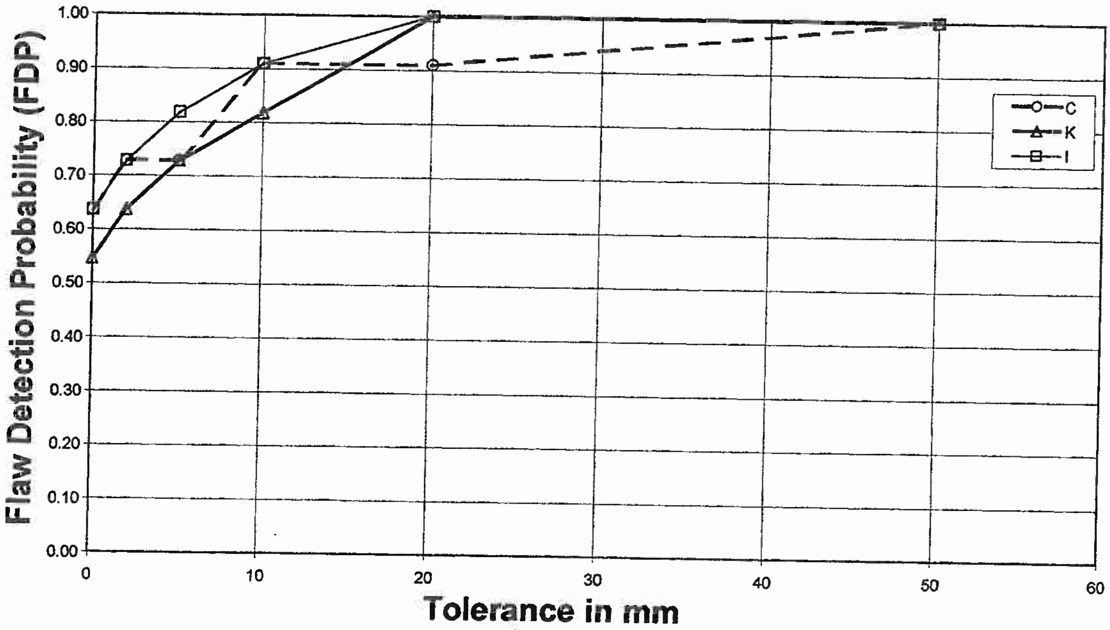


Figure 5 Detection as a function of the tolerance for defects C, K and I

2) As explained in section 5.3 where more details are given on the defects introduced in the cylinder the cladding area above most of the EDM notches and sub-clad cracking areas contained porosities. However, in the information package distributed prior to the inspection the teams were asked to look only for sub-clad defects. Therefore, it was agreed not to consider indications or parts of indications in the cladding in order to assess the inspection performance.

3) There were 3 groups of sub-clad cracks. In the information package supplied to the teams they were asked to detect and size each group as a single box and to give the size of the largest crack in the box. For those teams who provided grouped results the assessment was done as follows.

- Detection: if the grouped indication covers all individual cracks detection was attributed for all individual cracks.
- Length sizing: reference length was that of the combined cracks
- TWE sizing: the largest TWE of the individual cracks within a group was taken as the reference TWE

However, several of the teams gave details of the individual cracks present and so the DAG decided that where such detailed information was given it would be used in the analysis of detection and sizing performance for individual cracks.

4) The circumferential sub-clad cracks (F and P) were not included in the general analysis because the inspection teams had not been asked to look for this type of defects. Indications of teams, corresponding with these circumferential defects were consequently not considered. Circumferential false calls were also not considered.

5) The complex defect (H) was not included in the general assessment of the inspection results. Some inspection teams gave detailed information on the characteristics of this defect. Once the results of the destructive examination for this defect become available it is the intention to assess in more detail the inspection results for this defect.

6) Indications smaller than 3 mm not corresponding with any of the intended defects were not considered for assessing the false call performance.

7) Unintended defects, whose presence was confirmed through radiography and destructive examination, were not included in the general analysis. There were 5 such unintended defects. It follows that indications of teams corresponding with these unintended defects were also not considered. This affected the following 4 teams: EE, FF, GG and NN.

8) Areas, which had been excluded for inspection, were not considered. Indications, which corresponded with residual stress holes, were also not considered.

8 AMENDMENTS MADE TO THE TEAMS INSPECTION DATA

8.1 Description of procedure for the amendment of the data

In accord with the rules specified by the DAG two types of changes were made to the final inspection results when the data had been put into the BTB database. Briefly, these were:

1. The tabulated data in the "Boat" database were sent to each inspection team for confirmation that the results correctly represented the information submitted. At this stage, of course, the information on the defect parameters was still known only to the RL. Some inspection teams asked to have minor corrections made to the inspection data, such as for example, small shifts in location or small changes in dimensions. However, teams were not allowed to add or remove any indications. The changes were small and the DAG considered that since the team did not know the true defect parameters this was an acceptable change.

2. The second type of changes was made by the RL according to the DAG rules, which are described in more detail in the previous section. Broadly, this involved the removal of indications from the "Boat" data that corresponded to holes inserted for temperature and residual stress measurements, and removal from the "Train" data of information corresponding to circumferential defects, unintended defects and defects smaller than 3 mm. Also, the location of the crack tip at the cladding interface for sub-clad defects was normalised to the design thickness of the cladding.

8.2 Specific amendment of the data for the different teams

One specific change of note, which did not fall into the above categories listed in 8.1, was made by the RL with the approval of the DAG. The change was the amendment of the location of five defects, which had been reported by one team in the pre-test inspection. It was a systematic error of location of defects in the lower third of the cylinder. The DAG accepted that it was probable that human error had occurred in setting up the scanner; the impact of human error is discussed below.

Here follows a detailed overview of the other amendments that were made to the inspection data from each inspection team.

8.2.1 Amendments made to the data from team BB

Ident.	Submitted by	Reported change
Pre-Test Data:		
1	Team	Change Z_1 values for 1 indication (B) from 170 mm to 138 mm. The new value had been reported, but the value not correctly transferred to data sheet DS 5.2.
2	Team	Changes in Y for 1 indication, (K) [+ 3 deg.].
3	Referee Group	Removed 2 indications as they correspond with the circumferential reference defects (F, P), as they are not considered in the analysis.
4	Referee Group	Removed 2 indications, as they were circumferential false calls.
5	Referee Group	Removed 1 indication, as it was a false call < 3 mm in length.
6	Referee Group	Z2 corrections made to 1 indication (B). Values set to 171.5 mm (interface cladding/base-material).
Post-Test Data:		
7	Referee Group	Remove 2 indications as these corresponded with the two residual stress holes.
8	Referee Group	Z2 corrections made to 3 indications (G, I, L). Values set to 171.5 mm (interface cladding/base-material).
9	Referee Group	Removed 9 indications, as they were false call (< 3 mm in length).

Table 6 Table of amendments to the data reported by team BB.

8.2.2 Amendments made to the data from team CC

Ident.	Submitted by	Reported change
Pre-Test Data:		
1	Team	Change X values of 1 indication (I) to X_1 = 578 mm [+5 mm], X_2 = 633 mm [-5 mm].
2	Team	Change Z_1 of 1 indication (Q) Z_1 =163.5 [-3 mm].
3	Referee Group	Removed 1 indication as it corresponds with the circumferential reference defects (F), it is not considered in the analysis.
4	Referee Group	Z_2 corrections made to 3 indications (M, N, O). Values set to 171.5 mm (interface cladding/base-material).
Post-Test Data:		
5	Referee Group	Removed 1 indication as it corresponds with the circumferential reference defects (F), it is not considered in the analysis.
6	Referee Group	Z_2 corrections made to 3 indications (M, N, O). Values set to 171.5 mm (interface cladding/base-material).

Table 7 Table of amendments to the data reported by team CC.

The changes to the pre-test data submitted by the team (1+2) was found when comparing the pre-test and post-test data. The data was submitted together with the post test results.

8.2.3 Amendments made to the data from team DD

Ident.	Submitted by	Reported change
Pre-Test Data:		
1	Referee Group	Move 5 indications (C, D, E, G, L) [#1]
2	Referee Group	Remove 2 false call indications as both were outside the inspection area.
3	Referee Group	Corrected Z_2 values for 10 indications. Values set to 171.5 mm (interface cladding/base-material).
Post-Test Data:		
4	Referee Group	Remove 2 indications as these corresponded with the two residual stress holes.
5	Referee Group	Corrected Z_2 values for 10 indications. Values set to 171.5 (interface cladding/base-material).

Table 8 Table of amendments to the data reported by team DD

[#1] *During the pre-test inspection team DD had made an error of location for defects C, D, E (Hot Cracking defects), and G and L (EDM notches) by a distance between 50 and 70 mm. However, the position of these 5 indications, as given by Team DD, and their measured length suggest very strongly that Team DD did indeed detect these defects but with an error of location (see Figure J6 in Appendix 3 containing the BTB-plots). That is why for these defects the TG1-DAG group attributed detection for team DD.*

8.2.4 Amendments made to the data from team EE

Ident.	Submitted by	Reported change
Post-Test Data:		
1	Referee Group	Remove 2 indications as these corresponded with the two residual stress holes.
2	Referee Group	Removed 1 other indication that corresponded with an unintended defect (J').
3	Referee Group	Corrected Z_2 values for 11 indications. Values set to 171.5 mm (interface cladding/base-material).

Table 9 Table of amendments to the data reported by team EE.

Team EE did not inspect the whole cylinder, hence they did not detect defect (L, M, N and O)

8.2.5 Amendments made to the data from team FF

Ident.	Submitted by	Reported change
Post-Test Data:		
1	Referee Group	Remove 2 indications as these corresponded with the two residual stress holes.
2	Referee Group	Removed 1 indication as it corresponds with the circumferential reference defects (F), it is not considered in the analysis.
3	Referee Group	Removed 2 other indications that corresponded with unintended defects (F'+ J').

Table 10 Table of amendments to the data reported by team FF.

8.2.6 Amendments made to the data from team GG

Ident.	Submitted by	Reported change
Post-Test Data:		
1	Team	Changes in Y for 1 indication, (K) [< 1 deg.].
2	Team	Change Z_1 of 1 indication (L), $Z_1 = 168.5$ [-3 mm].
3	Referee Group	Remove 2 indications as these corresponded with the two residual stress holes.
4	Referee Group	Removed 1 other indication that corresponded with an unintended defect (J').

Table 11 Table of amendments to the data reported by team GG.

8.2.7 Amendments made to the data from team JJ

Ident.	Submitted by	Reported change
Post-Test Data:		
1	Team	An indication was added as biggest facet of the complex defect (H). However, this defect is not considered in this report.
2	Referee Group	Corrected Z_2 values for 2 indications (A, K). Values set to 171.5 mm (interface cladding/base-material).

Table 12 Table of amendments to the data reported by team JJ.

1.1.1 Amendments made to the data from team KK

Ident.	Submitted by	Reported change
Pre-Test Data:		
1	Referee Group	Corrected Z_2 value for 1 indication (RL). Value set to 175.5 mm.
Post-Test Data:		
2	Referee Group	Corrected Z_2 value for 1 indication (RL). Value set to 175.5 mm.

Table 13 Table of amendments to the data reported by team KK.

8.2.8 Amendments made to the data from team MM

Ident.	Submitted by	Reported change
Pre-Test Data:		
1	Team	Small change in position for most indications in X, Y and Z. The changes for the pre-test data was submitted together with the post test inspection results
2	Team	Correct all Z_2 values to 171.5 mm
3	Referee Group	Removed 2 indications as they correspond with the circumferential reference defects (F, P), as they are not considered in the analysis.
Post-Test Data:		
4	Team	Correct all Z_2 values but two to 171.5 mm Correct the Z_2 values for the last 2 indications (B, RL) to 175.5 mm.
5	Referee Group	Removed 2 indications as they correspond with the circumferential reference defects (F, P), as they are not considered in the analysis.

Table 14 Table of amendments to the data reported by team MM.

8.2.9 Amendments made to the data from team NN

Ident.	Submitted by	Reported change
Pre-Test Data:		
1	Team	Correction of Y for 2 indications (H, N). The corrections had been reported, to the RL before the post-test
2	Referee Group	Removed 1 indication that corresponded with an unintended defect (N').
Post-Test Data:		
3	Referee Group	Removal of 2 indications as they correspond with residual stress holes.
4	Referee Group	Removed 1 indication that corresponded with an unintended defect (N').

Table 15 Table of amendments to the data reported by team NN.

8.2.10 Amendments made to the data from team TT

Ident.	Submitted by	Reported change
Pre-Test Data:		
1	Team	Change of Z_1 for defect B to 86 mm. The new value had been reported, but not correctly transferred to data sheet DS 5.2. Defect H not Through-wall Extent sized, but this defect is not evaluated in this report.
2	Referee Group	Corrected Z_2 values for all indications. Values set to 171.5 mm (interface cladding/base-material).

Table 16 Table of amendments to the data reported by team TT.

1.1.2 Amendments made to the data from team LL and SS

No amendments were made to the data of team LL and SS. These teams performed only additional sizing on data recorded by a different team of some of the larger defects.

9 ASSESSMENT OF THE DETECTION AND FALSE CALLS PERFORMANCE

9.1 Detection performance in the pre-test inspection

All the inspection data included in the analysis from the pre-test inspections are from ultrasonic inspections. The results of the one team that carried out an Eddy Current inspection could not be used in the analysis, because of the large number of false calls.

The detection rates achieved by the pre-test inspection teams are represented in . Five of the seven teams detected all the defects. The two teams not achieving 100% detection were (The through-wall extent of the defects in mm. is given in parenthesis):

- Team BB, which was the only team that used an exclusively manual inspection procedure, did not detect four EDM defects, A (5.5), L (2.5), G (13.5), and Q (6.5).
- Team, CC, which did not detect defects A (5.5) and L (2.5).

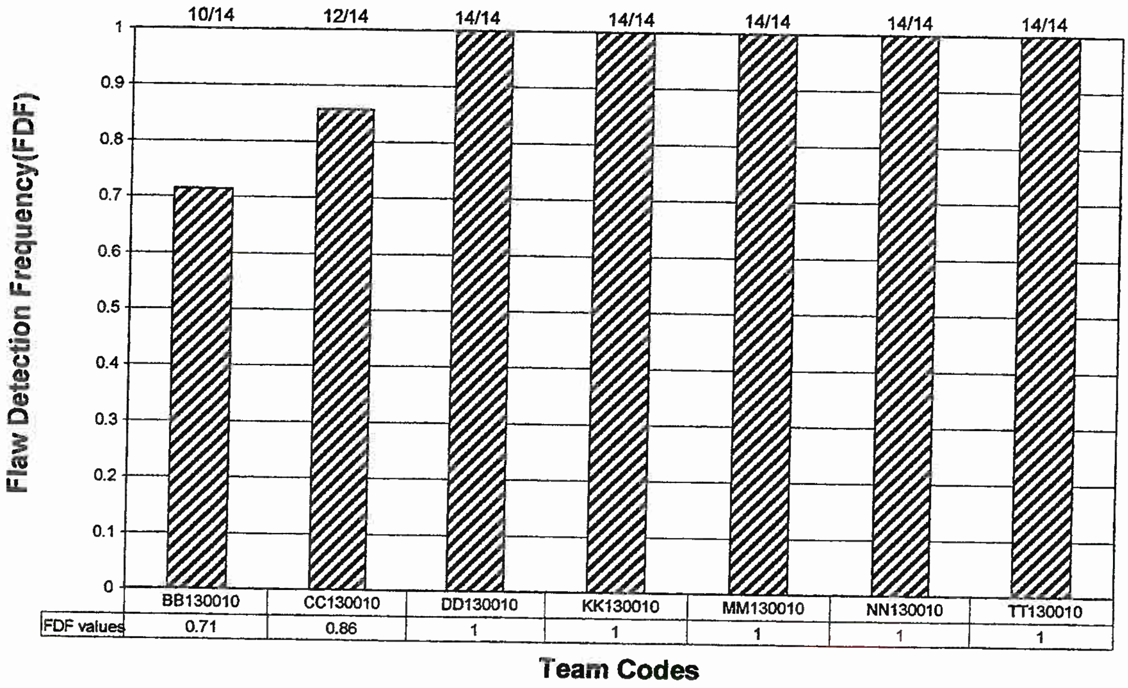


Figure 6 Detection Frequency of teams participating in the pre-test inspection

9.2 Detection performance in the post-test inspection

Ten teams used ultrasonic inspection techniques in the post-test inspections and two teams used eddy current techniques. Team KK performed a full inspection with both detection and sizing during the pre-test inspection. However, as was permitted under the rules, they performed only resizing during the post-test inspection. The detection rates achieved are represented in . Eight of the ten teams that used ultrasonic techniques detected all the defects. The two teams not achieving 100% detection was:

- Team (CC) did not report the EDM defects A (5.5) and L (2.5), as was also the case for this team in its pre-test inspection.
- The second team (DD) missed a group of realistic underclad cracks, C (5.5), D (7.5), E (6.5) and an EDM notch, G (13.5); it is important to note, however, that team DD did detect these defects in the pre-test inspection. Since the team was using the same equipment and procedures, this result suggests strongly that some kind of human error may have occurred. This proposal is supported by the observation that the four missed defects are all located in the lower part of the cylinder, suggesting that an error may have occurred in re-positioning the scanner for operation over this region. This team is also the team that had a significant shift made to its data on defect location in the pre-test inspections.

Another team (EE) did not inspect the whole cylinder due to time restraints for their inspections. However, they obtained full detection in the area of the cylinder they inspected (11 of 11 defects).

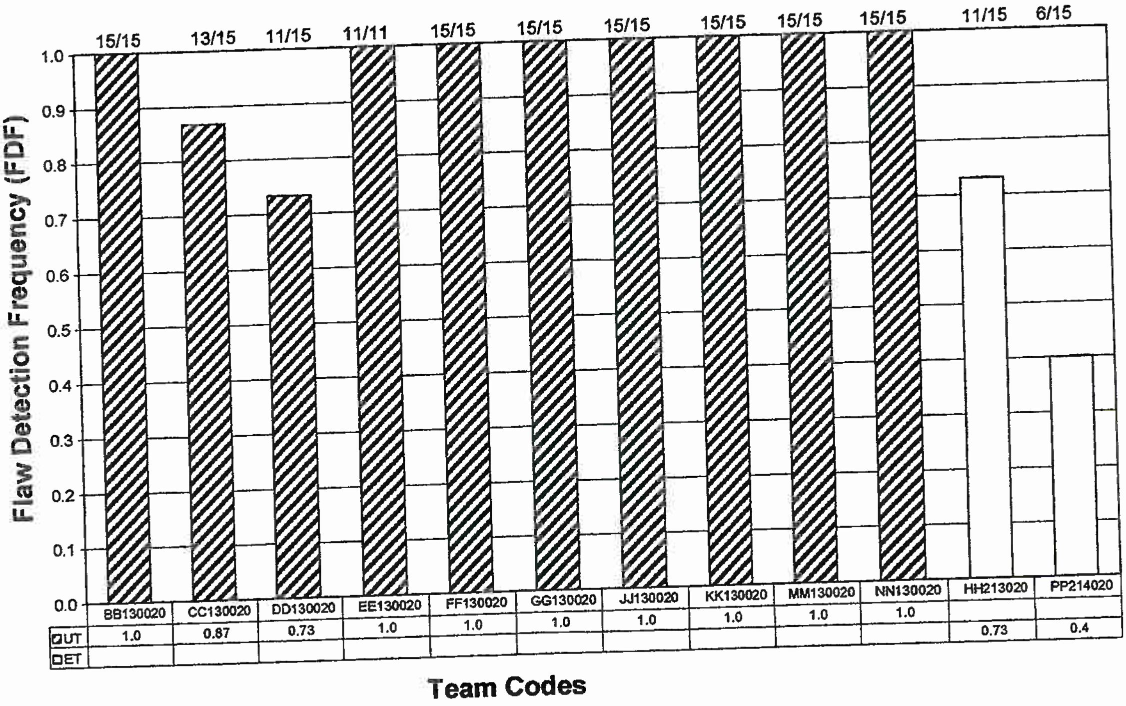


Figure 7 Flaw Detection Frequency of teams participating in the post-test inspection.

Also, it is important to note that a third team (BB) that detected all the defects in this phase of the inspections missed four defects in the pre-test inspections. Information provided to the RL after completion of the inspections indicated that some training had been given to the inspectors and an additional member had joined the team for the second phase of inspections, and this may have contributed to the improvement.

The detection results obtained by the two team s using eddy current techniques are below the detection performance reached by the ultrasonic inspection teams. One of the eddy current inspection teams detected 11 of the 15 defects and the other team detected only 6. It must be recognised that the defects in the NESC 1 cylinder were not entirely suitable for eddy current inspection techniques. Firstly, the smooth planar EDM defects (PISC type A) were inserted into the ferritic base-material by spark erosion, and were subsequently cladded by a 2-layer austentic strip cladding. The fused welded area at the cladding interface (melted structure of ferritic and austenitic material) acted as metallic bridge with increased magnetic permeability and represented an electrical short circuit above the notches, and thus affecting the detection performance. Secondly, the hot and cold cracking defects were three defect-groups represented by implanted areas with cracks. The change in structure between the implanted areas and the surrounding basematerial could easily be recognised with eddy current techniques, but these signals strongly reduced the capability to differentiate the different defects in the 3 defect-groups. Finally, it must also be acknowledged, that the implant configuration was not present in the eddy current calibration specimens and the algorithm used to process the data could not be optimised accordingly.

9.3 Comparison of the detection performance between the pre-test and the post-test inspection

Six inspection teams (all using ultrasonic inspection techniques) participated in both the pre-test and post-test inspection. A seventh team had two different inspection vendors subcontracted to perform the two inspections. The two inspection vendors have in this report been given different team codes. The inspection report from the team performing the pre-test inspection, was made available for the post-test inspection team. Both teams had a detection rate of 100%.

- Three of these teams obtained the same detection results during the pre- and post-test inspection.
- Team KK did not perform detection in the post-test inspection, but only did re-sizing as requested by the RL.
- Team BB detected 4 defects during the post-test inspection, which it missed during the pre-test inspection. They achieved thus a 100% detection rate in the post-test inspection.

- Team DD missed 4 defects during the post-test inspection, which it had detected during the pre-test inspection.

9.4 False call performance in the pre-test and the post-test inspection.

One team (BB) reported a number of small point indications in the pre-test inspection that did not correspond with any of the intended defects. The TG1-DAG decided that these point indications were so small that they should be excluded from the analysis. Apart from this, none of the pre-test inspection teams made any false calls.

In the post-test inspections, nine of the ten teams using ultrasonic techniques made no false calls. Team DD made 9 false calls mainly located in the lower part of the cylinder. As already discussed in 9.2, it is considered that this team possibly made an error in re-positioning the scanning equipment for scanning the lower part of the cylinder and this may be a contributing factor for the relatively high false call rate.

The two Eddy Current teams, HH and PP, made 3 and 7 false calls, respectively. Two of the 3 false calls made by team HH and 4 out of the 7 false calls made by team PP were reported as being located entirely within the cladding. As the teams were not required to report defects in the cladding these defects were not included in the analysis. Further, it must be recognised that the Eddy Current techniques are capable of picking up micro-structural changes in the materials.

The false call performances of the post-test inspection teams are plotted in Figure.

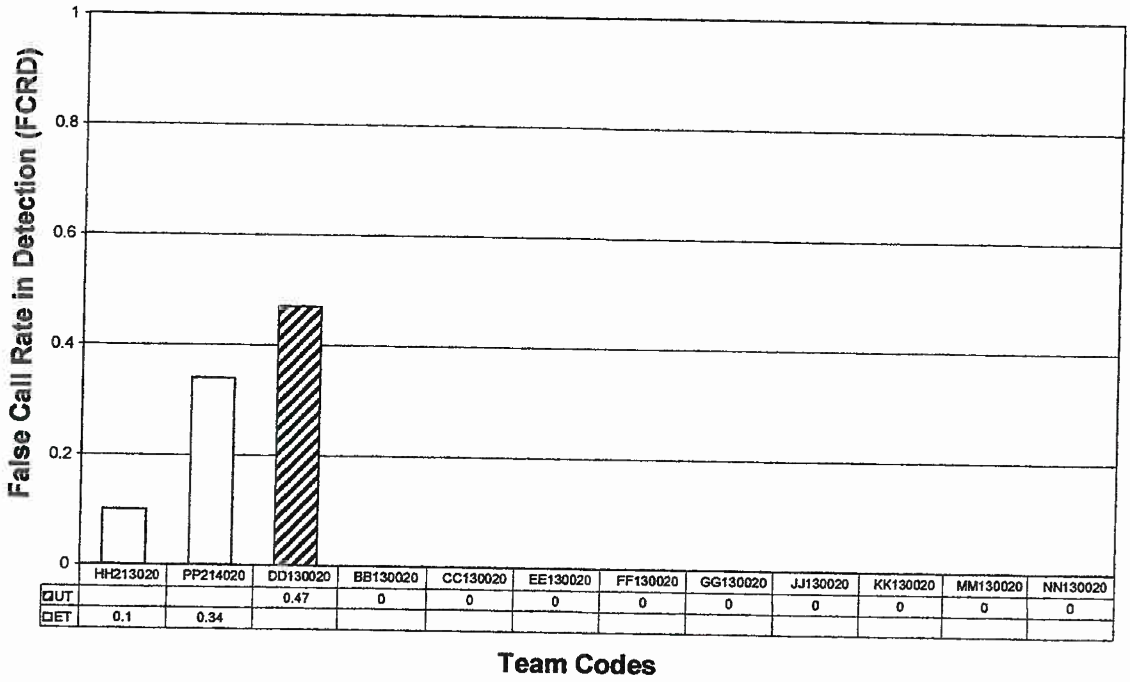


Figure 8 False Call Rate, quantified by the parameter FCRD, for the post-test inspection teams.

9.5 Inspection performance in general (detection and false call)

Detection rate is plotted versus false call rate for the pre-test inspections in Figure and for the post-test inspections in . In this type of presentation the y-axis relates to the safety of an inspection and the x-axis relates to the potential cost of unnecessary repairs. In the figures, optimum performance is located in the upper left corner of the figures (FDF > 0.8 and FCRD < 0.2). From Figure and it is clear that for 5 of the 7 pre-test inspection teams and 9 of the 12 of the post-test teams performance is excellent, i.e., all defects detected and no false calls. All of these teams used ultrasonic techniques. The performances of the teams using Eddy Current techniques were not as good.

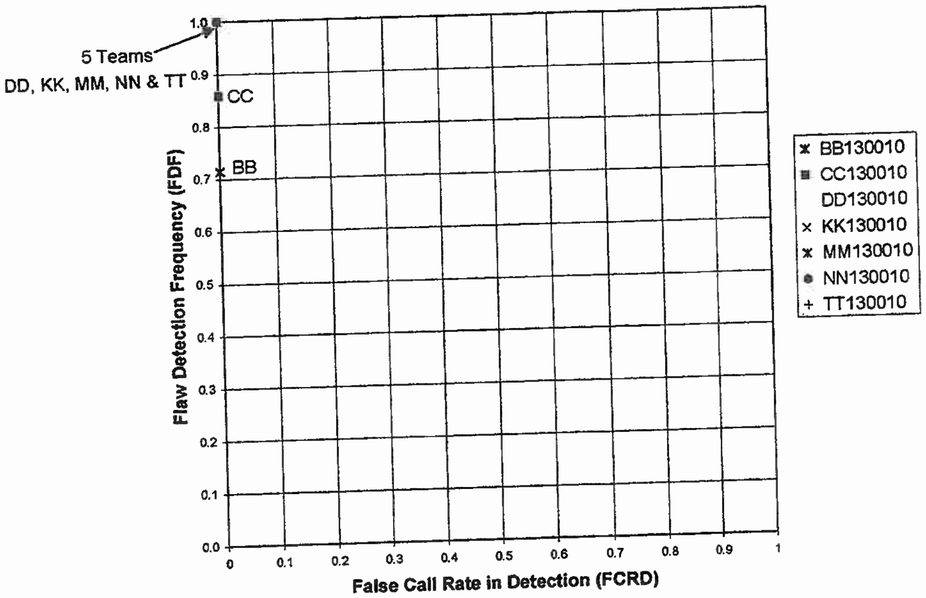


Figure 9 Detection Frequency (safety) versus False Call Rate in Detection (economical aspects) for the pre-test inspection teams

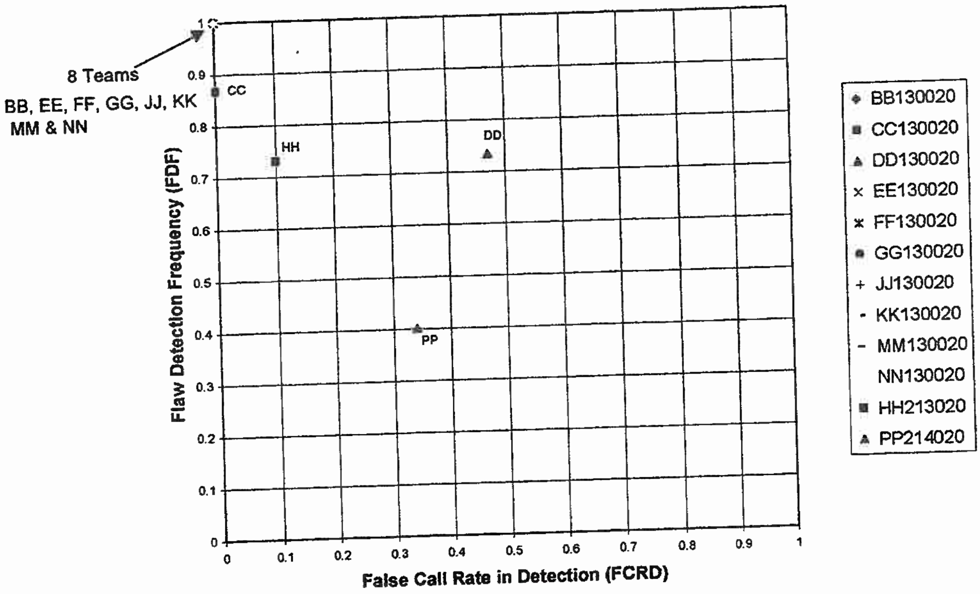


Figure 10 Detection Frequency (safety) versus False Call Rate in Detection (economical aspects) for the post-test inspection teams

10 ASSESSMENT OF THROUGH-WALL EXTENT SIZING

10.1 Through-wall extent sizing performance for the pre-test inspection

In Figure the reference through-wall extent of the defects, obtained by destructive examination, is plotted versus the values measured and reported by the different teams. This shows that five teams achieved good sizing of the large sub-clad fatigue crack (defect B), but two teams undersized it substantially.

The sizing performance for defects sized between 0 and 30 mm is given in Figure 1 and this shows that sizing accuracy was good for some teams but that others teams significantly undersized this range of defects. For defects below 10 mm, there was a significant range of both under- and oversizing.

The results for each inspection team are given in Appendix 5 of Part 2 of this report.
These give a clear indication of the individual performances of each team. From the results it is clear that four teams (CC, KK, MM, NN) achieved very good sizing of the TWE of the defects. In particular, the results of team KK are outstanding and must be considered to be leading edge technology, which would be hard to better. Teams CC and MM are also very good. Team NN sized most of the defects well but appear to have experienced some difficulty with some of the defects in the size range 4 to 8 mm; this may be a problem stemming from the grouping of the smaller defects. A fifth team, TT, sized the large defect well but experienced difficulties with all the smaller defects, reporting them all as the same size. Information supplied by the team indicated that different sizing techniques had been used for the two size ranges, with SAFT processing of the tip-diffracted wave being employed for the large defect and some other for the smaller defects. It is considered possible that the technique used for the smaller defects was based on amplitude drop methods, which for defects smaller than the width of the insonifying beam can measure the beam width rather than the defect size. If this were the case then it would demonstrate the importance of selecting the correct sizing technique for the task in hand. The remaining two teams in general undersized the defects, particularly the large defects. Further specific observations can be made:

Furthermore, in Appendix 6 histograms are given in which the reference TWE size is compared with TWE sizes given by the different inspection teams for each individual reference defect.

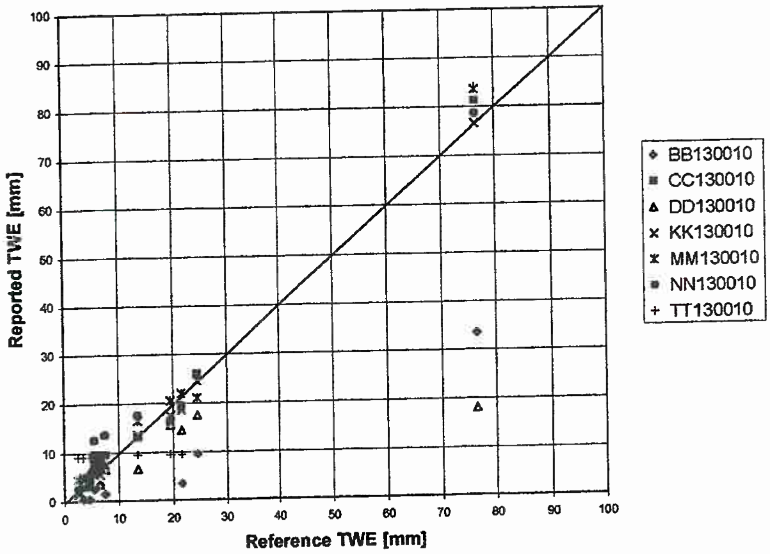


Figure 11 Measured TWE versus Reference TWE for all defects in pre-test inspections

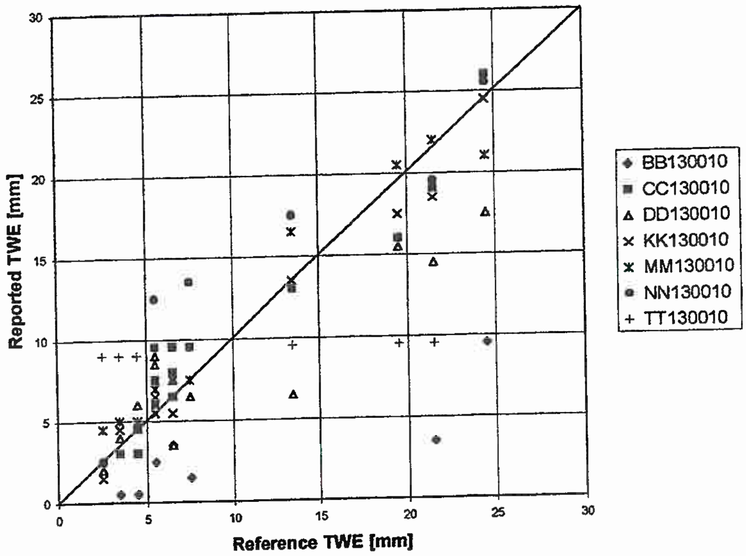
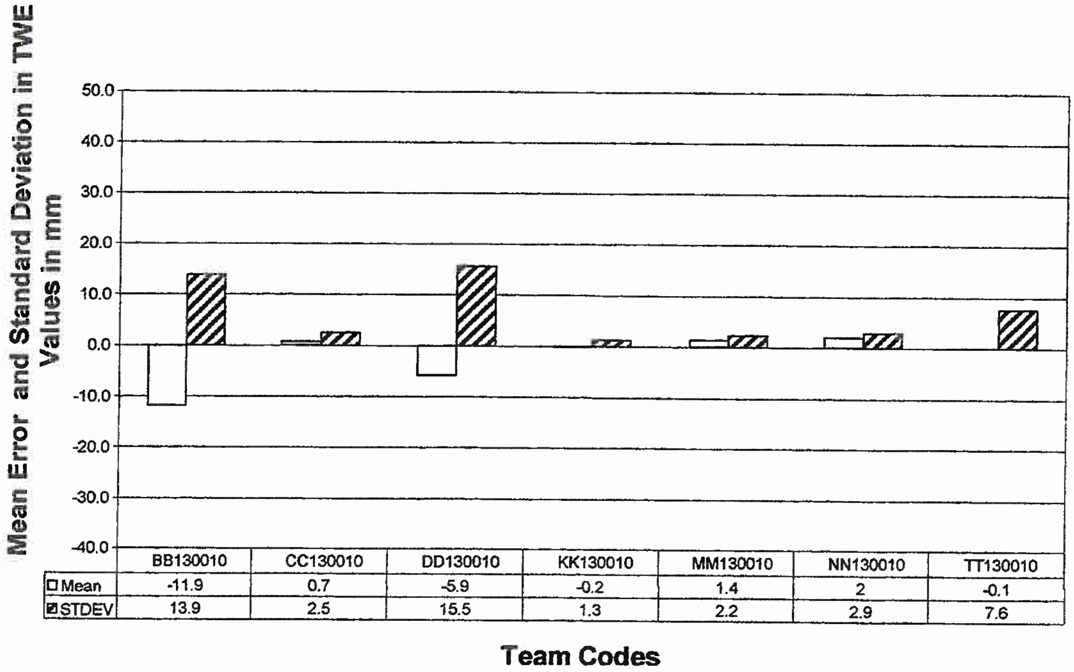


Figure 12 Measured TWE versus reference TWE for all defects with a TWE below 30 mm in pre-test inspections

Figure 13 shows that 4 of the 7 teams achieved good accuracy, in sizing all the defects, having a mean error of 2 mm or less, and a standard deviation of less than ±3 mm. The fifth team had also had a good mean error result of 0.1 mm, but a standard deviation of ±7.6 mm, this was due the sizing performance of the smaller defects. The two remaining teams however showed significant undersizing of most of the defects in their pre-test inspections, including in particular the large sub-clad fatigue crack, and this is reflected in relatively large values of standard deviation.

To examine the influence of defect size on sizing accuracy the mean error and standard deviation for the pre-test inspection data for defects less than 30 mm are given in Figure 1. This shows that the excellent performance of the four good teams noted above is virtually unchanged, as is that of Team TT. The results for the remaining teams, BB and DD, however, improve significantly, particularly those of the latter team, BB, which effectively can now be categorized with the four good teams for this defect size range. Following discussion with Team DD it appears insufficient allowance was made in the scan design for the depth of coverage of the through-wall extent necessary for the two large defects, thus significant errors occurred in sizing these larger defects. This is considered to represent a human error at the design stage.



	BB130010	CC130010	DD130010	KK130010	MM130010	NN130010	TT130010
☐ Mean	-11.9	0.7	-5.9	-0.2	1.4	2	-0.1
▨ STDEV	13.9	2.5	15.5	1.3	2.2	2.9	7.6

Figure 13 Mean error and standard deviation in TWE sizing for pre-test inspections

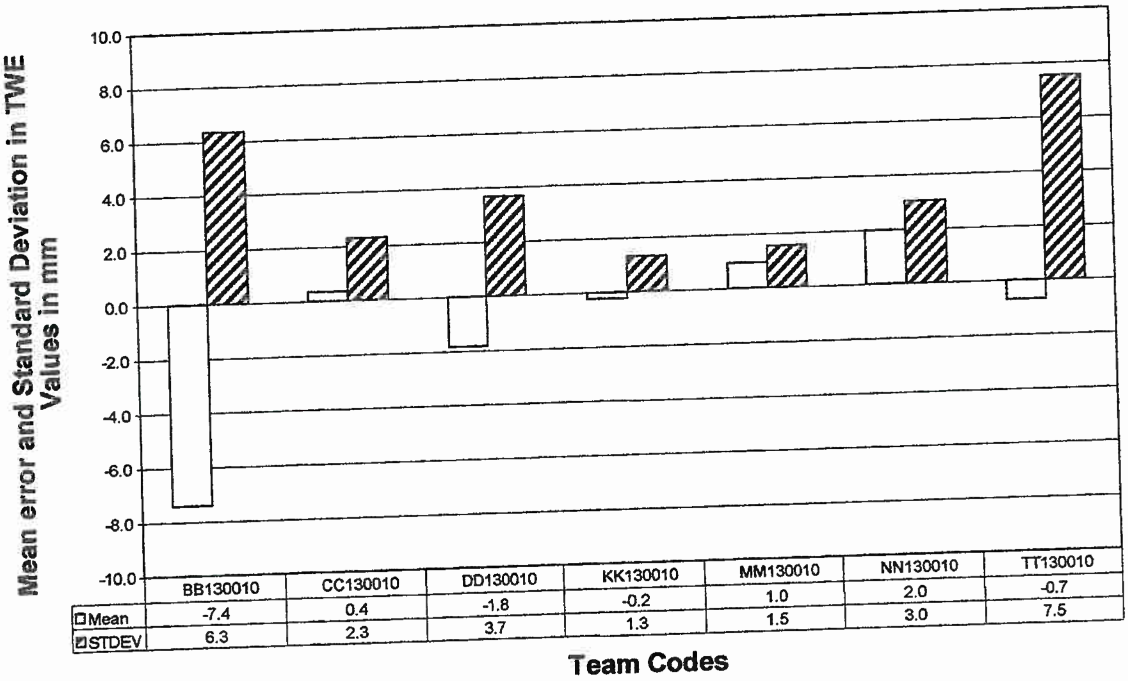
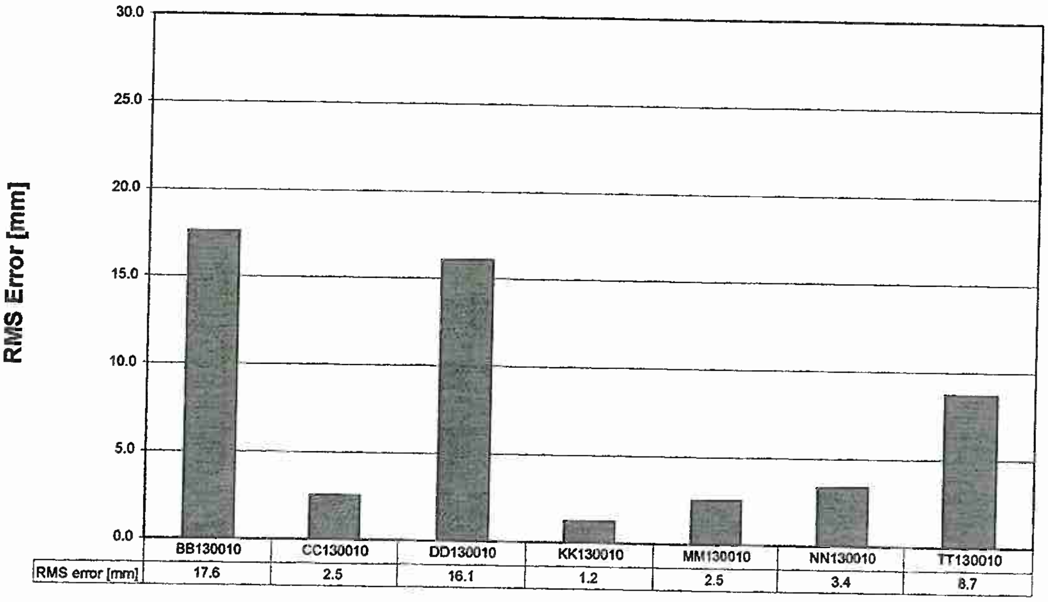


Figure 14 Mean error and standard deviation in TWE sizing for pre-test inspections considering only defects with a TWE below 30 mm.

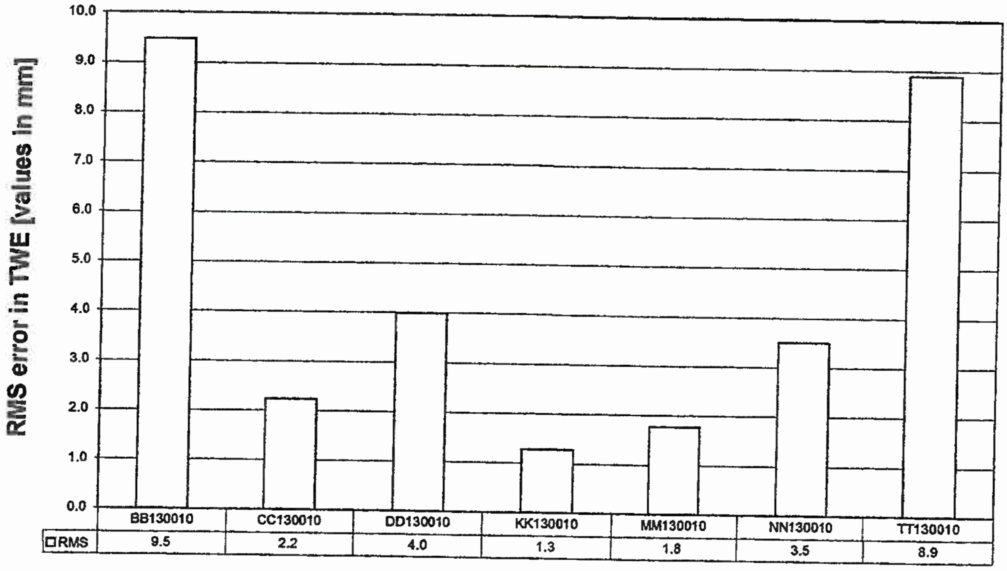
The RMS error for the pre-test teams on all defects is plotted in Figure . This analysis shows the same behaviour as that observed for standard deviation. When similar analysis is limited to defect sizes less that 30 mm, Figure , the changes are similar to those noted above for standard deviation, in that results for the four good teams remain virtually unchanged (also unchanged for team TT), but the RMS for team BB and DD noticeable improves, particularly that of team DD.

The maximum undersizing and oversizing are plotted in Figure 1 and , respectively. The letters at the top of each bar on these two figures refer to the specific defect for which the under- and oversizing occurred. The maximum oversizing tends to be relatively small but for undersizing the large through-clad defects dominates



	BB130010	CC130010	DD130010	KK130010	MM130010	NN130010	TT130010
RMS error [mm]	17.6	2.5	16.1	1.2	2.5	3.4	8.7

Figure 15 RMS error in TWE sizing for all pre-test inspections



	BB130010	CC130010	DD130010	KK130010	MM130010	NN130010	TT130010
□RMS	9.5	2.2	4.0	1.3	1.8	3.5	8.9

Figure 16 RMS error in TWE sizing for all pre-test inspections for pre-test inspections considering only defects with a TWE below 30 mm.

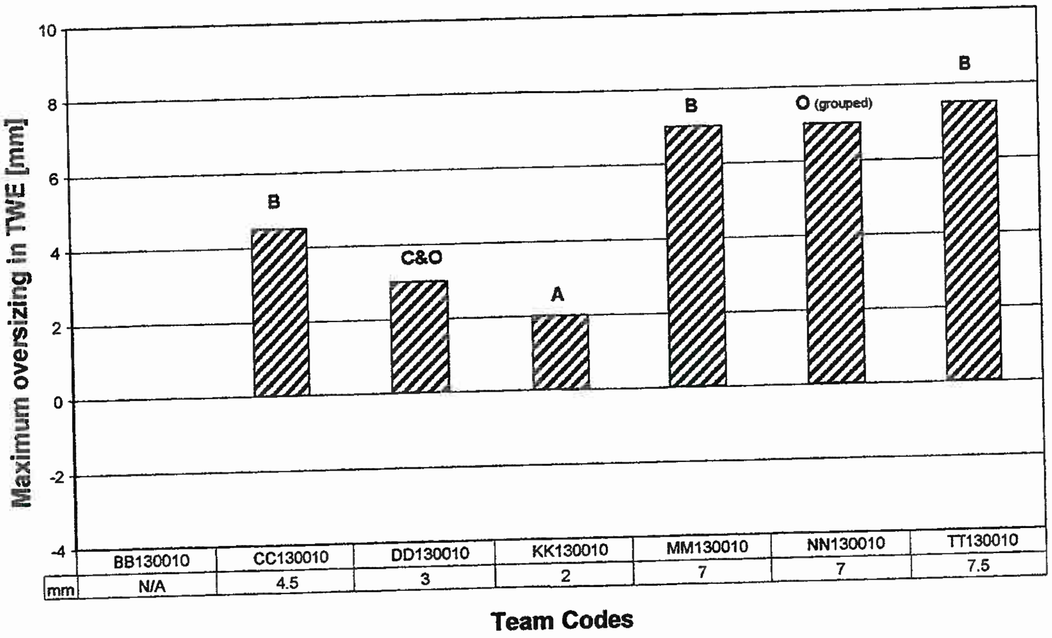


Figure 17 Maximum oversizing in TWE sizing for all pre-test inspections

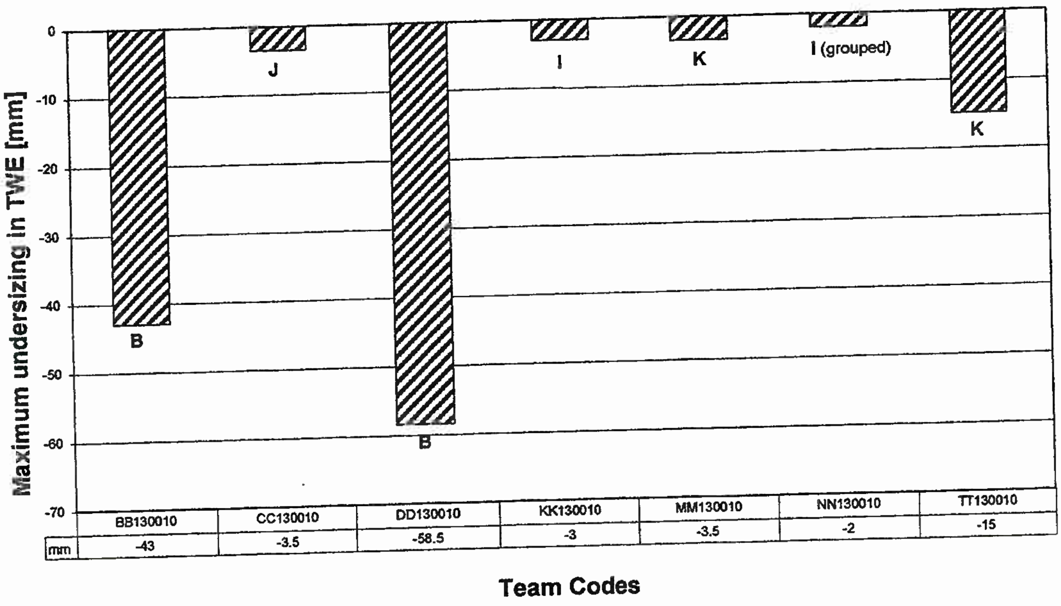


Figure 18 Maximum undersizing in TWE sizing for all pre-test inspections

10.2 Through-wall extent sizing performance for the post-test inspection

In Figure 19 the reference TWE size is plotted versus the TWE measured in the post-test inspections by the different teams. It shows that one team significantly undersized the two large defects (B and RL), which both had a through-wall extent of about 75 mm.

In Figure 20 the reported TWE is plotted versus the reference size for defects below 30 mm in TWE. Most teams perform well although a tendency to oversize the smaller defects of less than 10 mm is observed, but one team significantly undersized the smaller defects of the order of 5 mm, and another team undersized defects in the range 20 to 30 mm.

The results for each inspection team are given in Appendix 7 of Part 2 of this report. These give a clear indication of the individual performances of each team. From the data it is clear that eight teams achieved good results, with team KK being outstanding, as was CC and EE. Two teams, DD and JJ exhibited erratic sizing performance. Team DD sized the smaller defects well but grossly undersized the two large defects. This is similar to the team's performance in the pre-test inspection and is attributed to incorrect selection of the sizing technique parameter's at the design stage. Team JJ sized the two large defects well having showed a tendency to report the same size for the smaller defects, as team TT had done in the pre-test inspections. The remarkable improvement in the performance of team BB in the post-test inspection is discussed in Section 10.3 below.

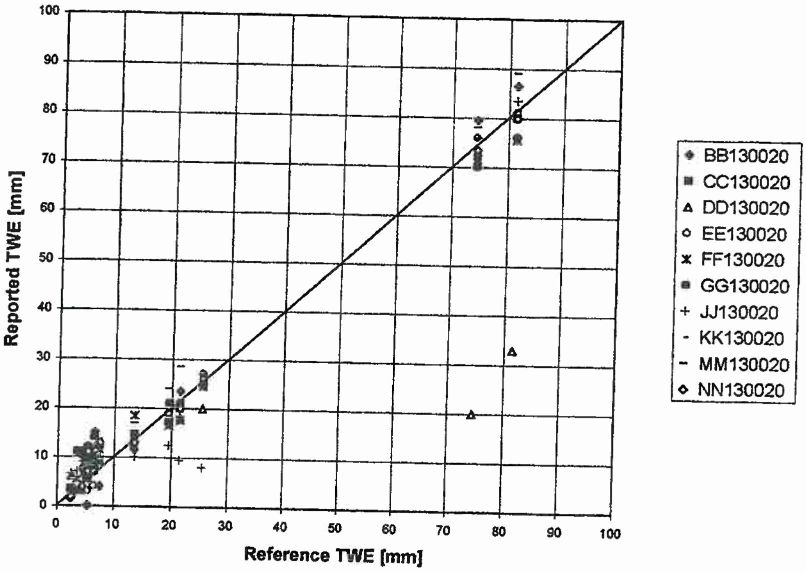


Figure 19 Measured TWE versus Reference TWE for all defects in post-test inspections

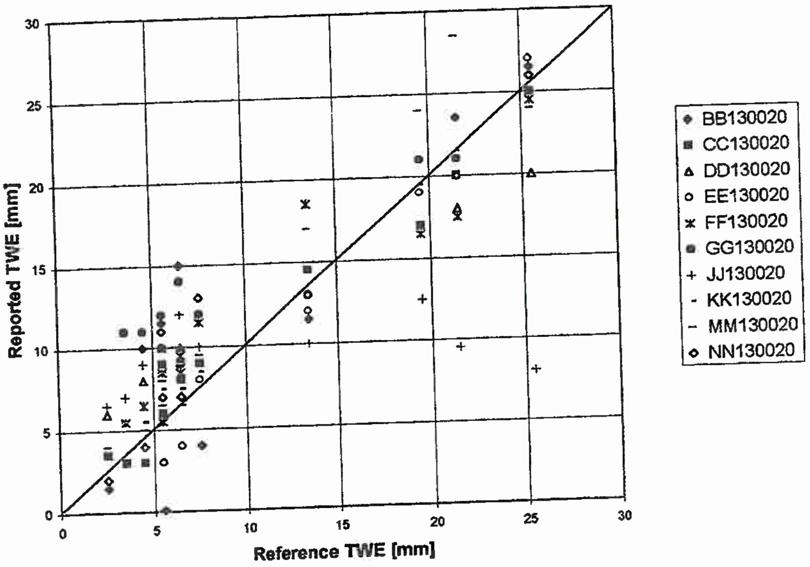
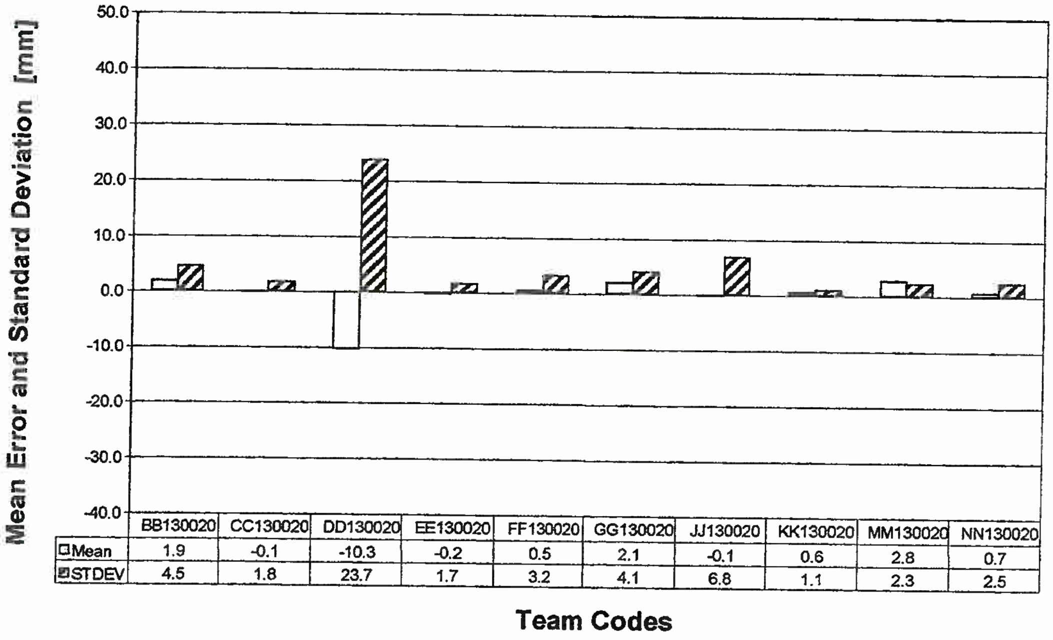


Figure 20 Measured TWE versus Reference TWE for all defects with a TWE below 30 mm in post-test inspections

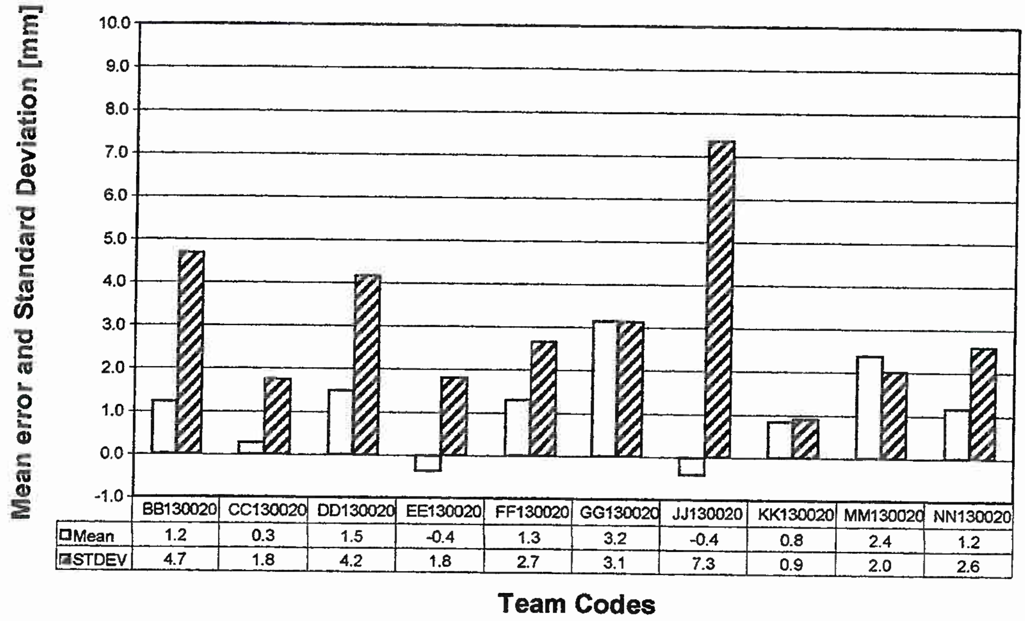
Figure 21 shows that 4 teams sized very accurately with a mean error of less than 1 mm and a standard deviation of ±2.5 mm or less. Five other teams achieved a similar mean error with a standard deviation better than 6.8 mm. The remaining team, as in its pre-test inspection, showed significant undersizing and a relatively large standard deviation.

The sizing accuracy's in the post-test inspections for defects less than 30 mm are shown in Figure 22. For 9 of the 10 teams the mean error and standard deviation do not change significantly, but the results for Team DD improve substantially; possible reasons for this have been advanced above. The RMS error for the same ranges of defects is shown in Figure and Figure and follows the same pattern of behavior.



	BB130020	CC130020	DD130020	EE130020	FF130020	GG130020	JJ130020	KK130020	MM130020	NN130020
□Mean	1.9	-0.1	-10.3	-0.2	0.5	2.1	-0.1	0.6	2.8	0.7
▨STDEV	4.5	1.8	23.7	1.7	3.2	4.1	6.8	1.1	2.3	2.5

Figure 21 Mean error and standard deviation in TWE sizing for post-test inspections



	BB130020	CC130020	DD130020	EE130020	FF130020	GG130020	JJ130020	KK130020	MM130020	NN130020
□Mean	1.2	0.3	1.5	-0.4	1.3	3.2	-0.4	0.8	2.4	1.2
▨STDEV	4.7	1.8	4.2	1.8	2.7	3.1	7.3	0.9	2.0	2.6

Figure 22 Mean error and standard deviation in TWE sizing for post-test inspections considering only defects with a TWE below 30 mm.

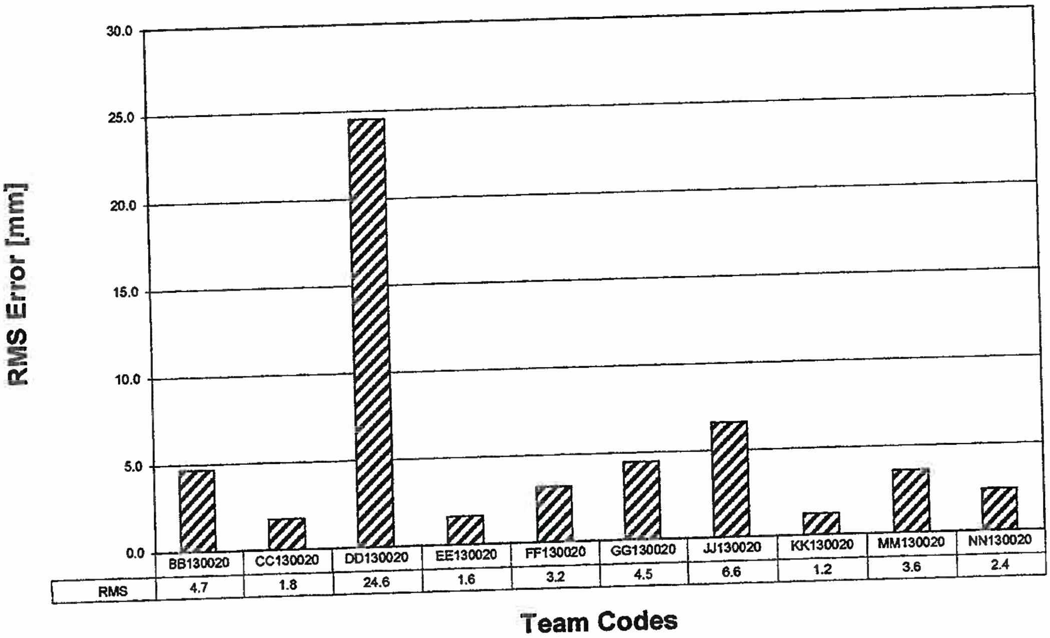


Figure 23 RMS error in TWE sizing for all post-test inspections

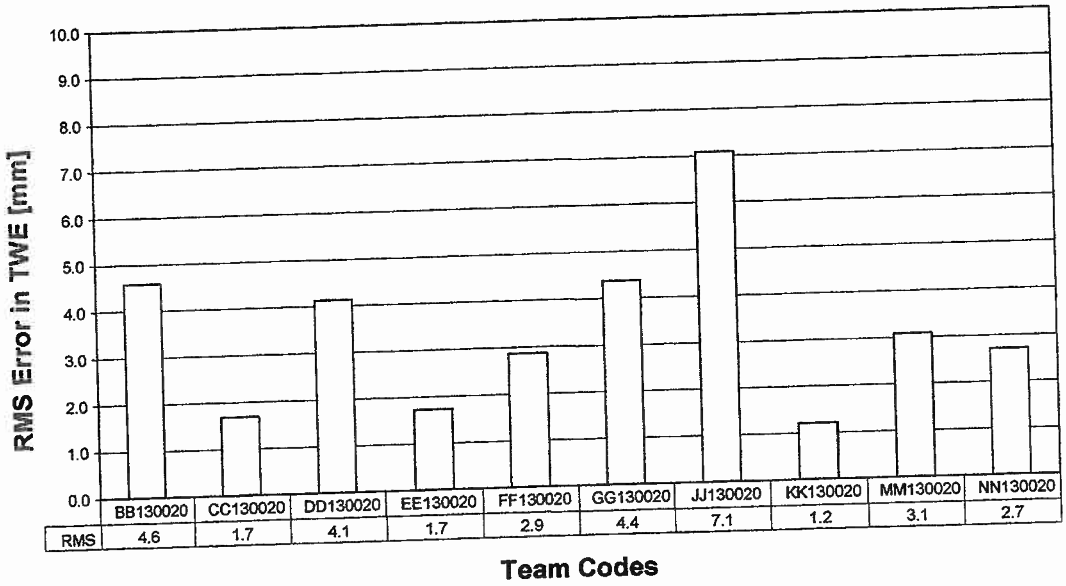


Figure 24 RMS error in TWE sizing for all post-test inspections considering only defects with a TWE below 30 mm.

The maximum undersizing and oversizing are plotted in Figure and Figure , respectively. The letters at the top of each bar on these two figures refer to the specific defect for which the under- and oversizing occurred. The maximum oversizing tends to be relatively small but for undersizing the large through-clad defects dominates

The good TWE sizing performance achieved by teams CC, EE, KK, and NN is confirmed by the values measured for the mean error, standard deviation and RMS error. The mean error varies between –0.1 mm and 0.7 mm, whereas the corresponding standard deviations are smaller than 3.0 mm. The RMS errors measured for these 4 teams are smaller than 3.0 mm and the maximum undersizing error made was only 2.5 mm. The maximum oversizing error made by these 4 inspection teams was 5.5 mm.

Note that also teams BB, FF, GG and MM had a relatively good TWE sizing performance. Their measured RMS error was smaller than 5.0 mm and the maximum undersizing was 6.0 mm. The mean error measured was also smaller than 3.0 mm with an associated maximum standard deviation of +/- -4.5 mm.

The fact that Team JJ undersized significantly the defects with a through-wall extent between 10 and 30 mm is reflected in the relatively large value of the RMS error of 6.8 mm and the relatively large mean error of 6.6 mm. The team's maximum undersizing was on defect K with a undersizing of 17.5 mm. Note that this team sized rather well the 2 larger cracks.

Team DD undersized significantly the larger cracks this is evidently reflected in all of the TWE sizing parameters.

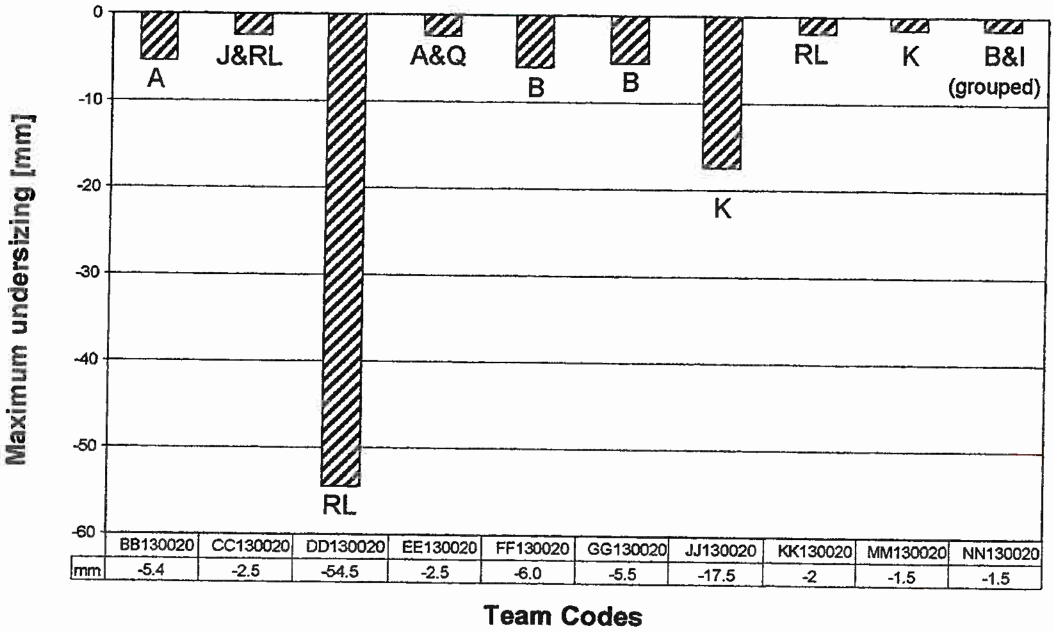


Figure 25 Maximum undersizing in TWE sizing for all post-test inspections

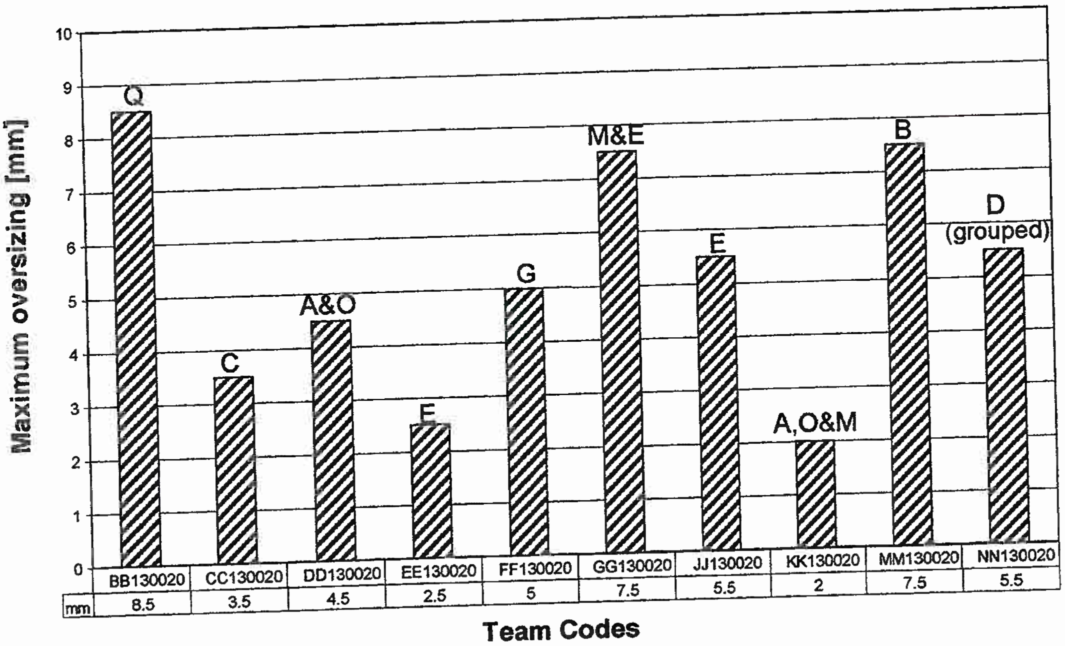


Figure 26 Maximum oversizing in TWE sizing for all post-test inspections

10.3 Comparison of the through-wall extent sizing performance between the pre- and the post test inspection

Not all the teams participated in both phases of the round robin inspections. The individual results for the six that did are given in Appendices 5 and 7 of Part 2 of this report for the pre and post-test inspections respectively. Four teams, (CC KK, MM. NN) achieved very good sizing results in both phases, with KK's results being excellent, as noted above, as were those of CC. Team NN tended to oversize some of the smaller defects in both phases, but nevertheless achieved good results. Team MM also showed a slight tendency to oversize.

Team BB exhibited some variability in sizing the smaller defects in both phases, but showed a remarkable improvement in sizing the large defects in the post-test inspections. This is attributed to some training being given to the team members between the inspection phases and a new member joining the team for the post-test inspection. DD had the same tendency to grossly undersize the large defects in both phases but showed some reduction in the undersizing of small defects post-test. The reason for the relatively poor TWE sizing results obtained by team DD on the larger defects is as previous described attributed to incorrect selection of the sizing technique parameter's at the design stage.

In Table 17 the TWE sizing performances of the teams which participated both in the pre-test and post-test inspection are compared.

Team	Time of inspection	Average error [mm]	Standard deviation [mm]	RMS-error [mm]	Max oversizing [mm]	Max undersizing [mm]
BB	Pre-test	-11.9	13.9	17.6	-3.0	-43
	Post-test	1.9	4.5	4.7	8.5	-5.4
CC	Pre-test	0.7	2.5	2.5	4.5	-3.5
	Post-test	-0.1	1.8	1.8	3.5	-2.5
DD	Pre-test	-5.9	15.5	16.1	3.0	-58.5
	Post-test	-10.3	23.7	24.6	4.5	-54.5
KK	Pre-test	-0.2	1.3	1.2	2.0	-3.0
	Post-test	0.6	1.1	1.2	2.0	-2.0
MM	Pre-test	1.4	2.2	2.5	7.0	-3.5
	Post-test	2.8	2.3	3.6	7.5	-1.5
NN	Pre-test	2.0	2.9	3.4	7.0	-2.0
	Post-test	0.7	2.5	2.4	5.5	-1.5

Table 17 Comparison between pre-test and post-test TWE sizing performance

From Table 17, it can be deduced that sizing of the TWE of the defects remained more or less the same for most teams, except for Team BB.

11 ASSESSMENT OF THE LENGTH SIZING PERFORMANCE

11.1 Length sizing pre-test inspection

In Figure the reference length, obtained by destructive examination, is plotted versus the length measured by the different inspection teams. In Figure the same plot is given considering only the defects with a length up to 80 mm.

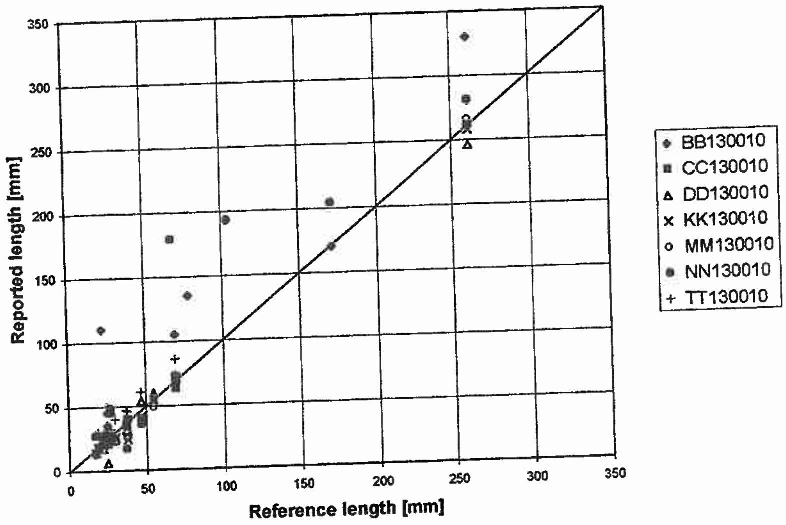


Figure 27 Measured length versus reference length for all defects in pre-test inspections

Figure 27 shows that four teams sized well, particularly team CC, although two of them undersized one defect. Two of the remaining teams significantly oversized several defects and one of these also undersized two defects. The seventh team (TT) consistently oversized all the defects.

In Figure 28 it can be seen that 2 teams (BB, NN) oversized considerably a number of defects. These defects are in general the grouped indications of real sub-clad cracking. Team DD undersized 1 of the smaller defects (defect D) significantly.

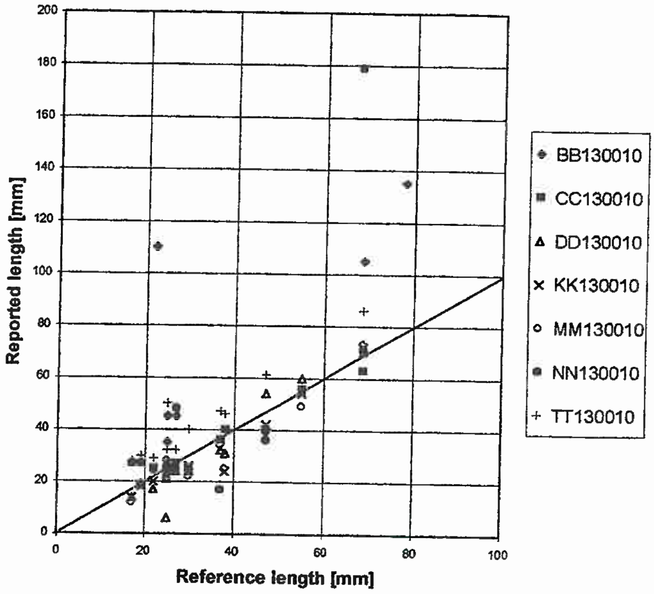
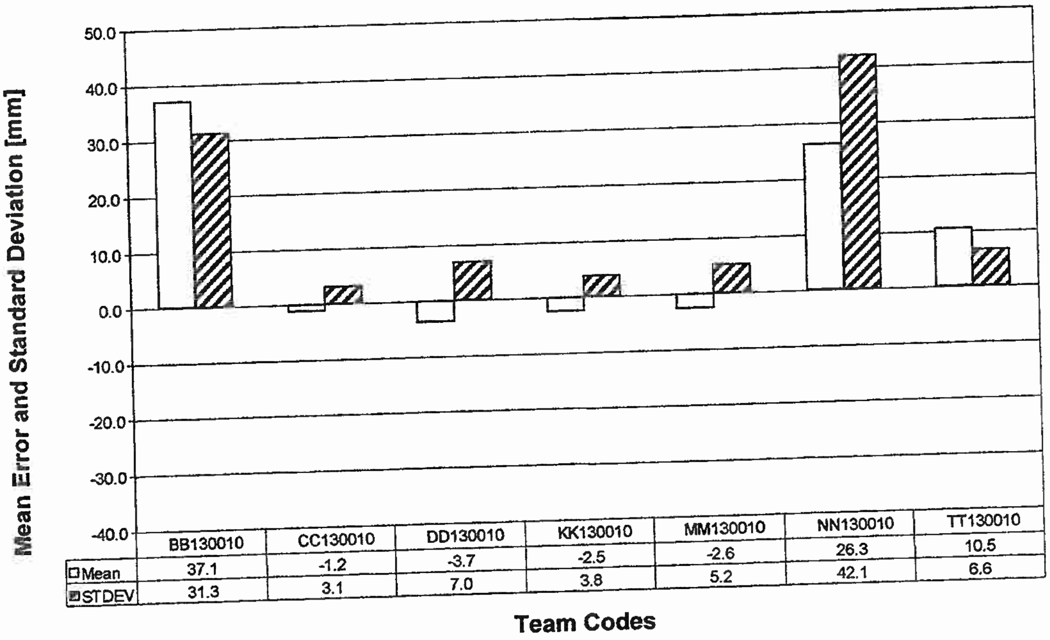


Figure 28 Measured length versus reference length for all defects with a length below 80 mm in pre-test inspections

Similar plots for the individual inspection teams are given in Appendix 9. Furthermore, in Appendix 10 histograms are given in which the reference length is compared with lengths given by the different inspection teams for each individual reference defect.

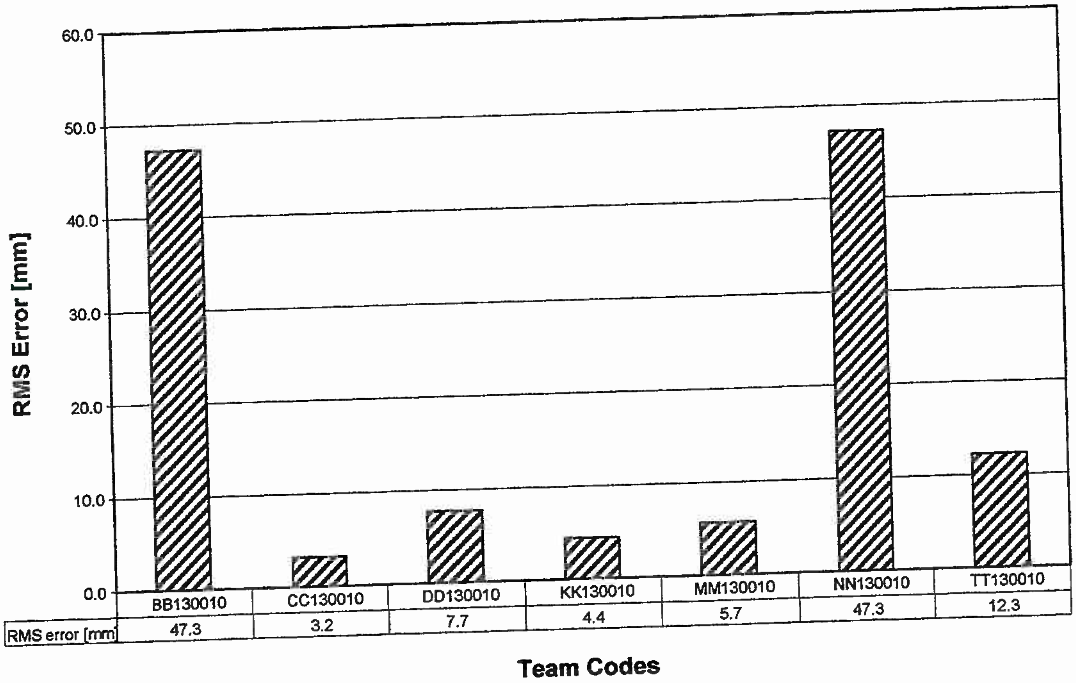
Figure 29 and Figure 30 shows the good length sizing performance achieved by teams CC, KK and MM is confirmed by the values shown. The mean error for these three teams varied between -1.2 mm and -2.5 mm, and the standard deviations were 5.5 mm or less: the RMS errors measured for these teams were less than 6 mm.

Figure 31 and Figure 32 shows the maximum oversizing error made by three teams CC, KK and MM was 5 mm or less and their maximum undersizing error was 14 mm. Team DD also had a generally good length sizing performance, although its maximum undersizing error was 20 mm. Team TT, and especially teams BB and NN, had relatively large oversizing errors, which are reflected in their performance parameters.



	BB130010	CC130010	DD130010	KK130010	MM130010	NN130010	TT130010
□ Mean	37.1	-1.2	-3.7	-2.5	-2.6	26.3	10.5
▨ STDEV	31.3	3.1	7.0	3.8	5.2	42.1	6.6

Figure 29 Mean error and standard deviation in length sizing for pre-test inspections



	BB130010	CC130010	DD130010	KK130010	MM130010	NN130010	TT130010
RMS error [mm]	47.3	3.2	7.7	4.4	5.7	47.3	12.3

Figure 30 RMS error in length sizing for all pre-test inspections

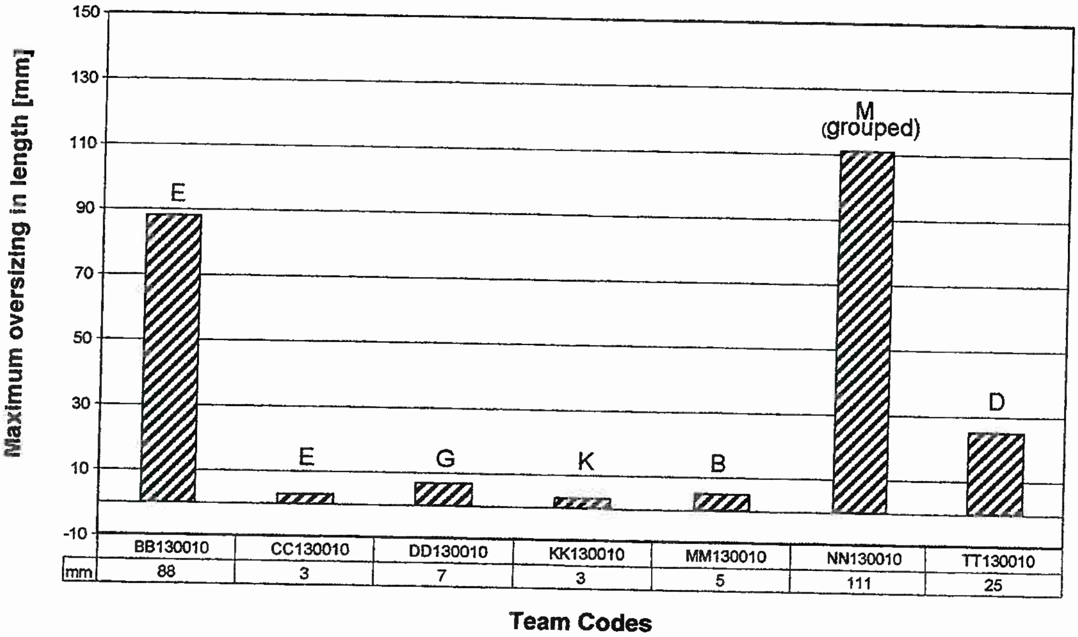


Figure 31 Maximum oversizing in length sizing for all pre-test inspections

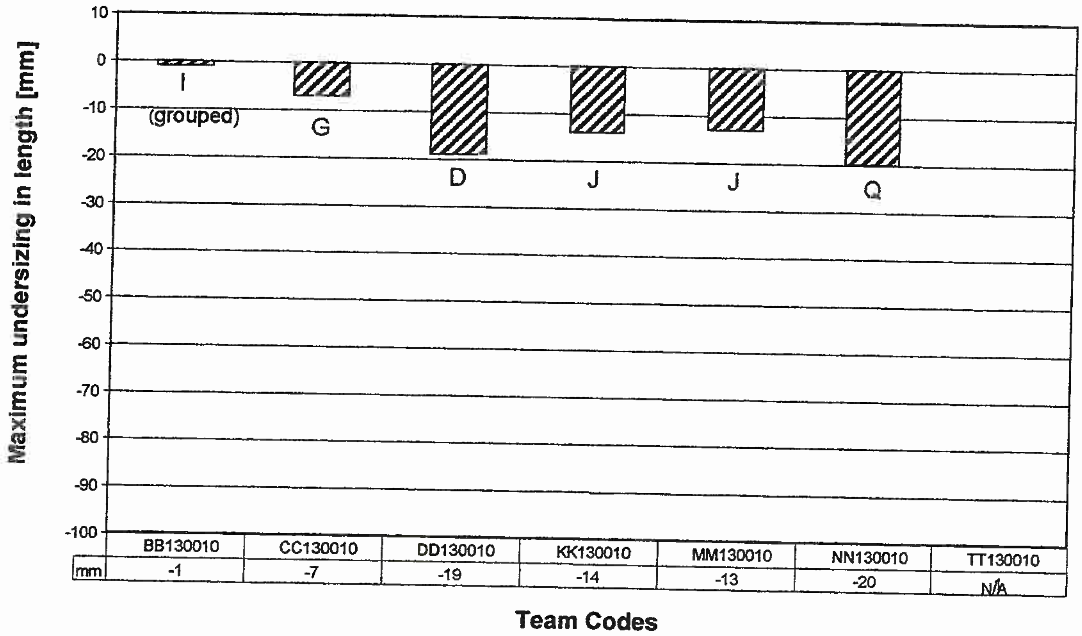


Figure 32 Maximum undersizing in length sizing for all pre-test inspections

It can be concluded that the teams that did better than average had a tendency for slight undersizing whereas the teams whose length sizing performance was below average oversized considerably some of the defects.

11.2 Length sizing post-test inspection

In Figure 33 the reference length, obtained by destructive examination, is plotted versus the length measured by the different teams. In Figure 34 the same plot is given considering only the defects which have a length up to 100 mm.

Figure 33 and Figure 34 shows that three teams CC, JJ and MM achieved excellent results, but three teams, BB, EE and NN, oversized the length of some of the defects significantly. The two eddy current teams HH and PP systematically undersized the length of all the defects.

Similar plots for the individual inspection teams are given in Appendix 11. Furthermore, in Appendix 12 histograms are given in which the reference length is compared with lengths given by the different inspection teams for each individual reference defect.

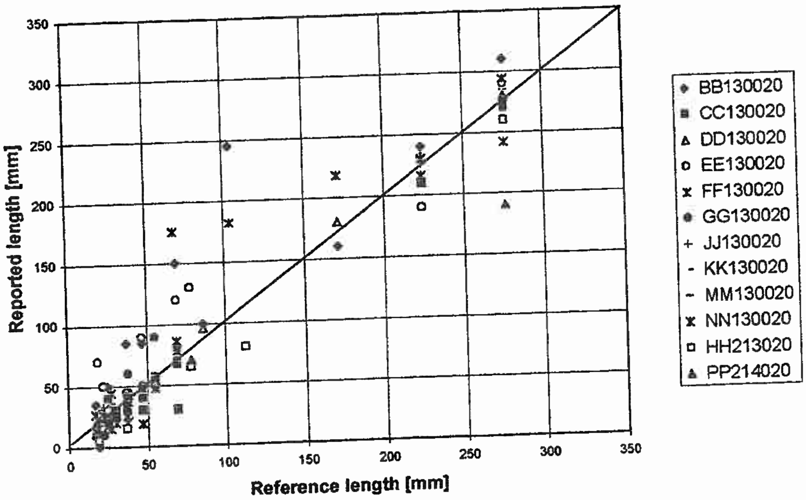


Figure 33 Measured length versus reference length for all defects in post-test inspections

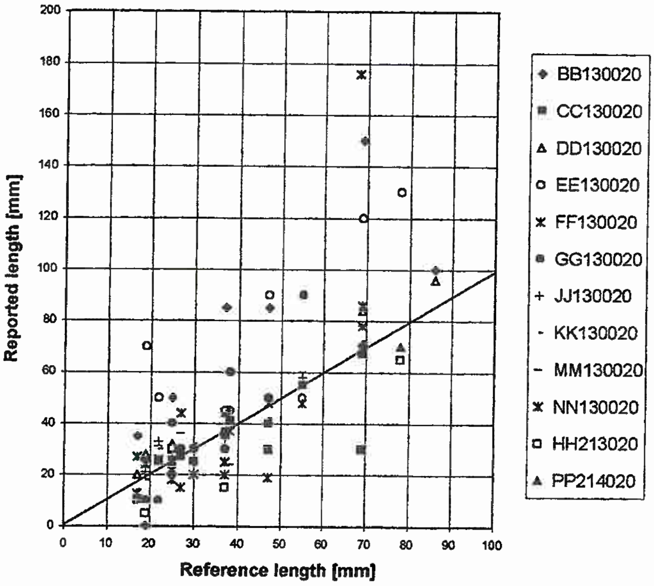
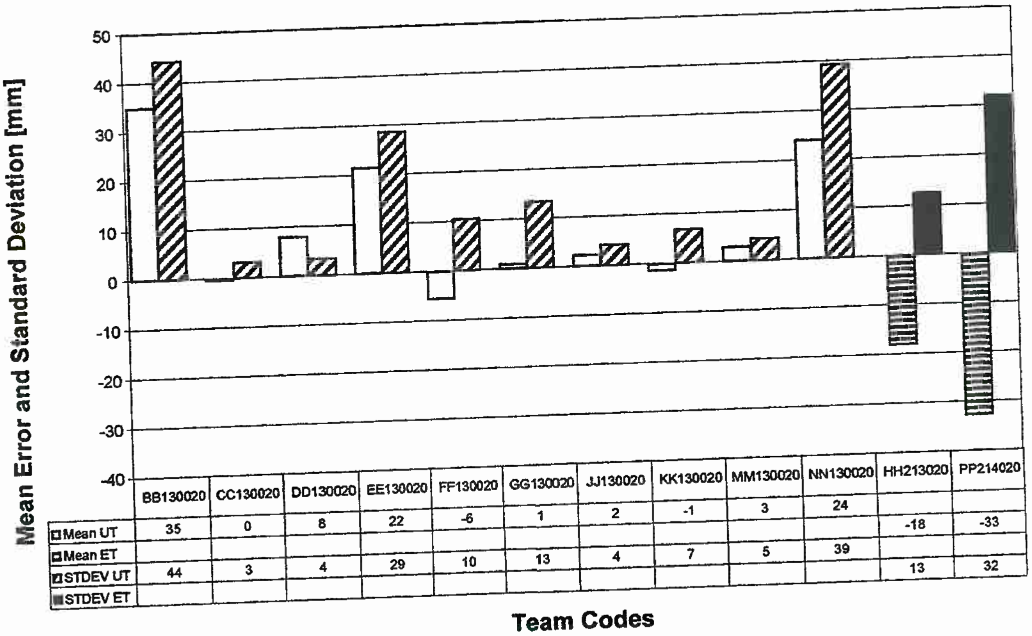


Figure 34 Measured length versus reference length for all defects with a length below 100 mm in post-test inspections

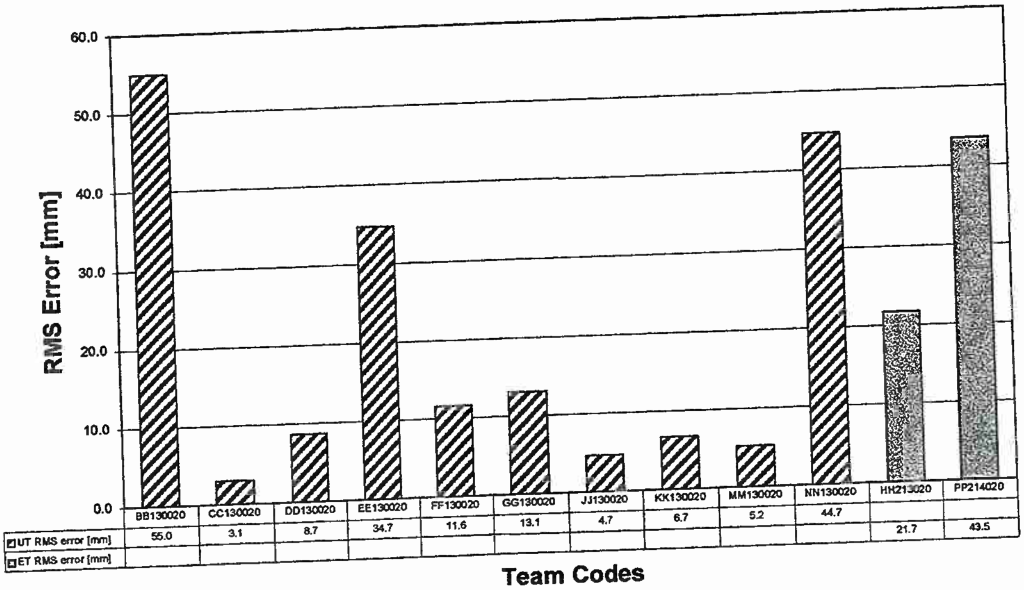
In Figure 35 and Figure 36 the mean error in length sizing with corresponding standard deviation and the RMS error for all the post-test inspection teams is plotted.

The excellent length sizing performance noted above for teams CC, JJ and MM is confirmed by the values measured for the mean error, standard deviation and RMS error. They have a mean error between 0 and 3 mm, the corresponding standard deviations were 5 mm or less, and their RMS errors were less than 6 mm. Their maximum undersizing error made was only 7 mm and the maximum oversizing error was 11 mm. Teams DD and KK also had relatively good post-. Their mean errors and RMS error was less than 9 mm, and their maximum standard deviation was 7 mm. Team EE had a less good test length sizing performance. They had a tendency to oversize most of the defect with a mean error of 22 mm and a corresponding standard deviation of 29 mm. The team sized the defects using single crystal shear wave transducers from the inside surface. Because of the existents of the dead zone in such type of probe the length sizing was performed in full skip of ultrasonic wave, thus some oversizing in length was expected. The remaining teams had maximum undersizing errors varying from 20 to 80 mm, with RMS errors larger than 10 mm, in some cases larger than 25 mm. The length sizing performance achieved by the two eddy current teams was below average as indicated by the RMS errors of about 20 and 40 mm, respectively. Both teams had a general tendency to undersize in length, as shown by their mean length sizing error of -18 mm and -33 mm, respectively.



	BB130020	CC130020	DD130020	EE130020	FF130020	GG130020	JJ130020	KK130020	MM130020	NN130020	HH213020	PP214020
☐ Mean UT	35	0	8	22	-6	1	2	-1	3	24		
☐ Mean ET											-18	-33
▨ STDEV UT	44	3	4	29	10	13	4	7	5	39		
■ STDEV ET											13	32

Figure 35 Mean error and standard deviation in length sizing for post-test inspections



	BB130020	CC130020	DD130020	EE130020	FF130020	GG130020	JJ130020	KK130020	MM130020	NN130020	HH213020	PP214020
▨ UT RMS error [mm]	55.0	3.1	8.7	34.7	11.6	13.1	4.7	6.7	5.2	44.7		
☐ ET RMS error [mm]											21.7	43.5

Figure 36 RMS error in length sizing for all post-test inspections.

The maximum oversizing and undersizing errors are plotted in Figure 37 and Figure 38, respectively

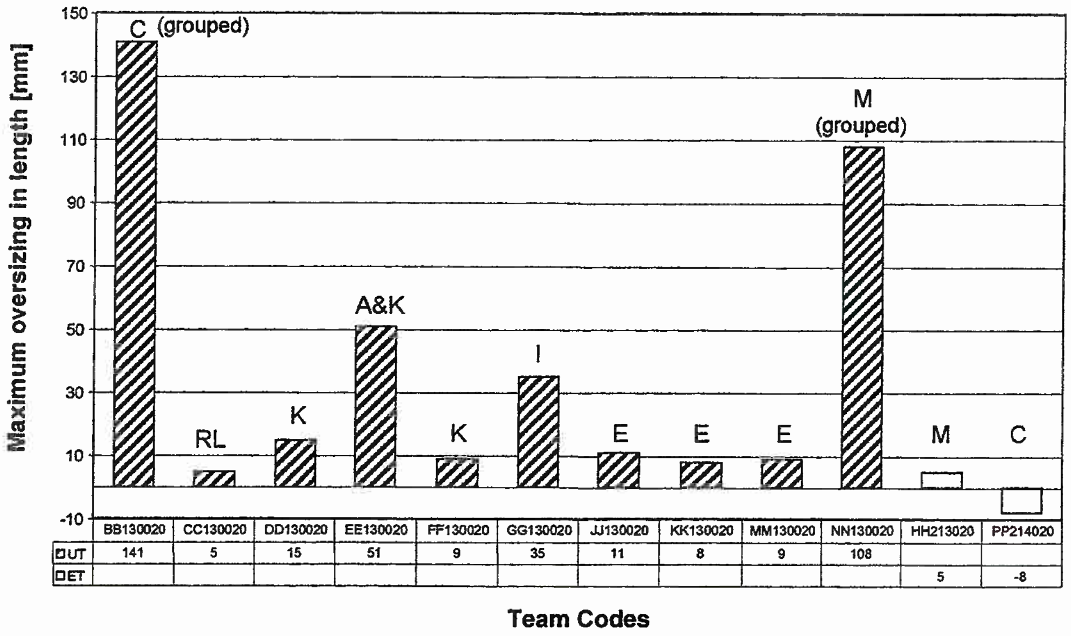


Figure 37 Maximum oversizing in length sizing for all post-test inspections

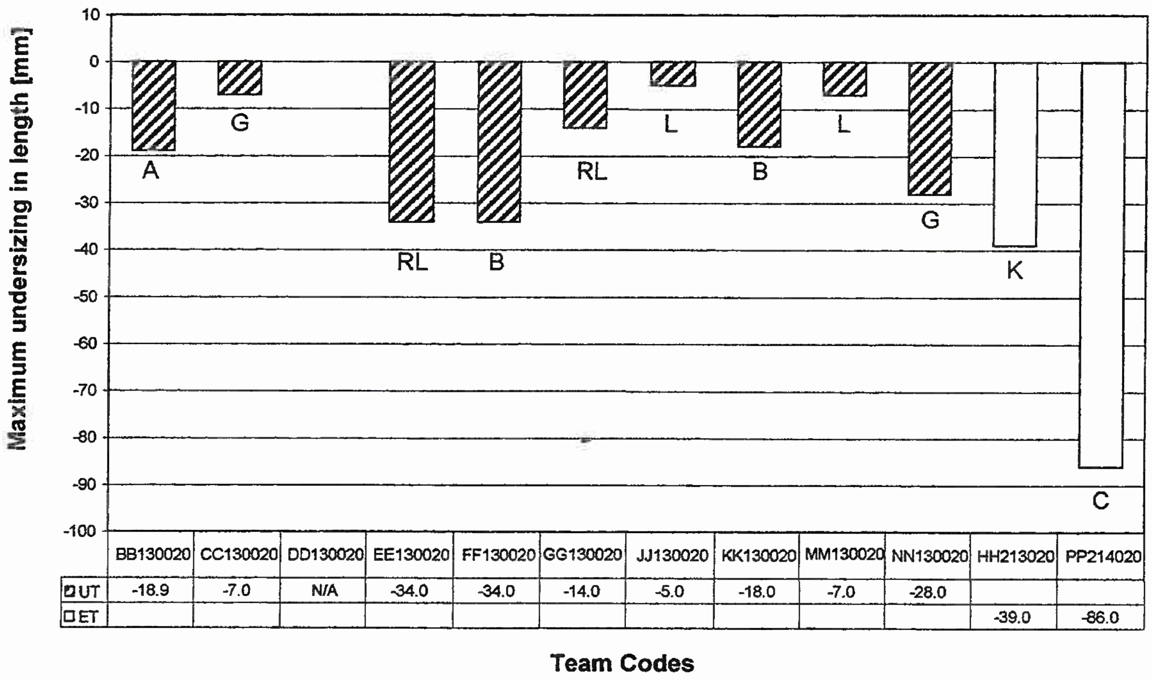


Figure 38 Maximum undersizing in length sizing for all post-test inspections

11.3 Comparison between pre- and post test length sizing performance

In Table 18 the length sizing performance of the teams that participated both in the pre-test and post-test inspection is compared.

Team	Time of inspection	Average error [mm]	Standard deviation [mm]	RMS-error [mm]	Max oversizing [mm]	Max undersizing [mm]
BB	Pre-test	37	31	47	88	-1
	Post-test	35	44	55	141[#1]	-19
CC	Pre-test	-1	3	3	3	-7
	Post-test	0	3	3	5	-7
DD	Pre-test	-4	7	8	7	-19
	Post-test	8	4	9	15	N/A
KK	Pre-test	-3	4	4	3	-14
	Post-test	-1	7	7	8	-18
MM	Pre-test	-3	5	6	5	-13
	Post-test	3	5	5	9	-7
NN	Pre-test	26	42	47	111[#1]	-20
	Post-test	24	39	45	108[#1]	-28

#1 Max oversizing value with grouped defects.

Table 18 Comparison between pre-test and post-test length sizing performance.

The maximum oversizing reported by team BB and NN (see note1 in Table 18) is occurring when they report neighbouring defects as a group, as permitted under TG1 rules

From Table 18 it can be deduced that the length sizing performance remained more or less the same for all teams. Note in this respect the outstanding good length sizing performance achieved by team CC.

12 ASSESSMENT OF MEASURED CRACK GROWTH

12.1 Crack growth in through-wall extent

Defect B grew by 5 mm in through-wall extent during the spinning cylinder test. The results reported by the teams for their measurements of the through-wall extent of Defect B in their pre- and post-test inspections is shown in Figure 39. The difference between the pre-and post-test through-wall measurements for each team is shown in Figure 40.

Two of the six teams (KK, MM), who participated in both phases measured the through-wall crack growth of Defect B extremely accurately, reporting 5 mm and 5.5 mm respectively. Note one of these teams KK reported the exact measurements determined by destructive examination. A third team reported a small crack growth of 1.5 mm and a fourth indicated a 1 mm shrinkage. It should be emphasised that the sizing performance reached by these four teams is probably among the best that is currently technically possible.

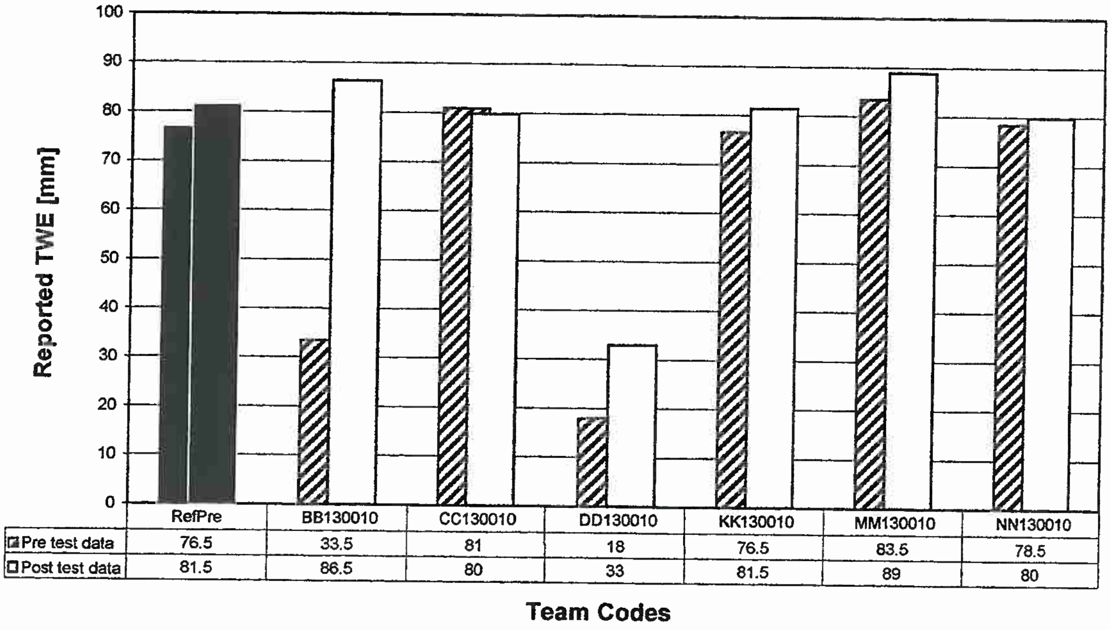


Figure 39 Comparison of pre- and post-test TWE of defect B as measured by the teams who participated in the pre- and post-test inspections

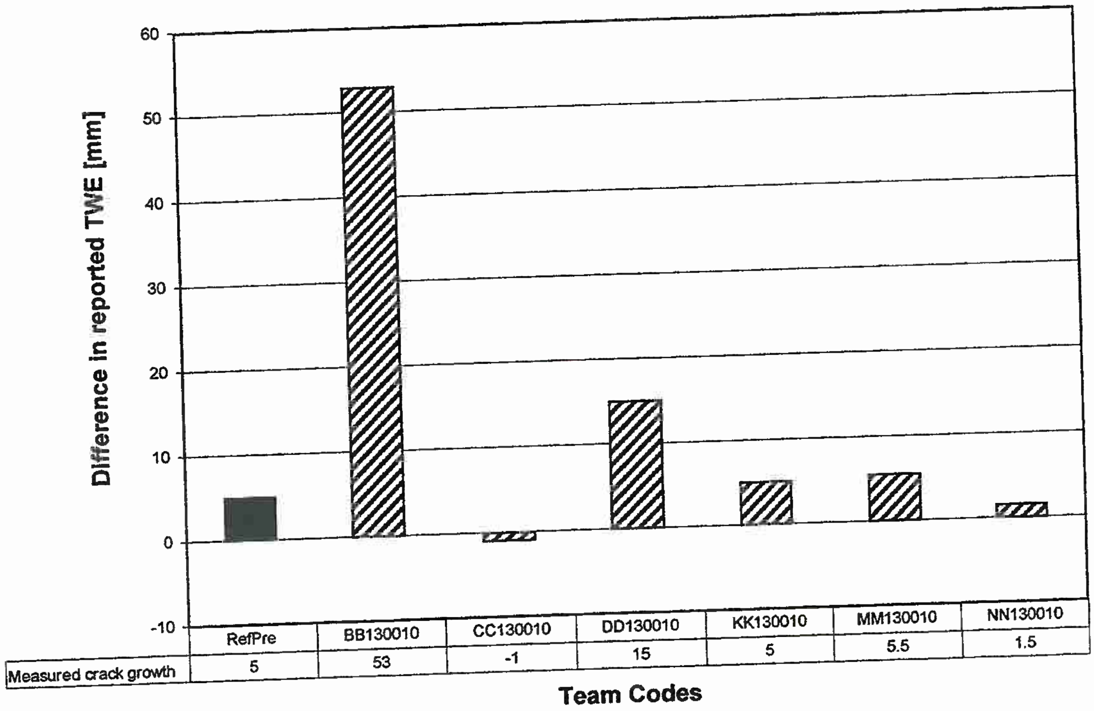


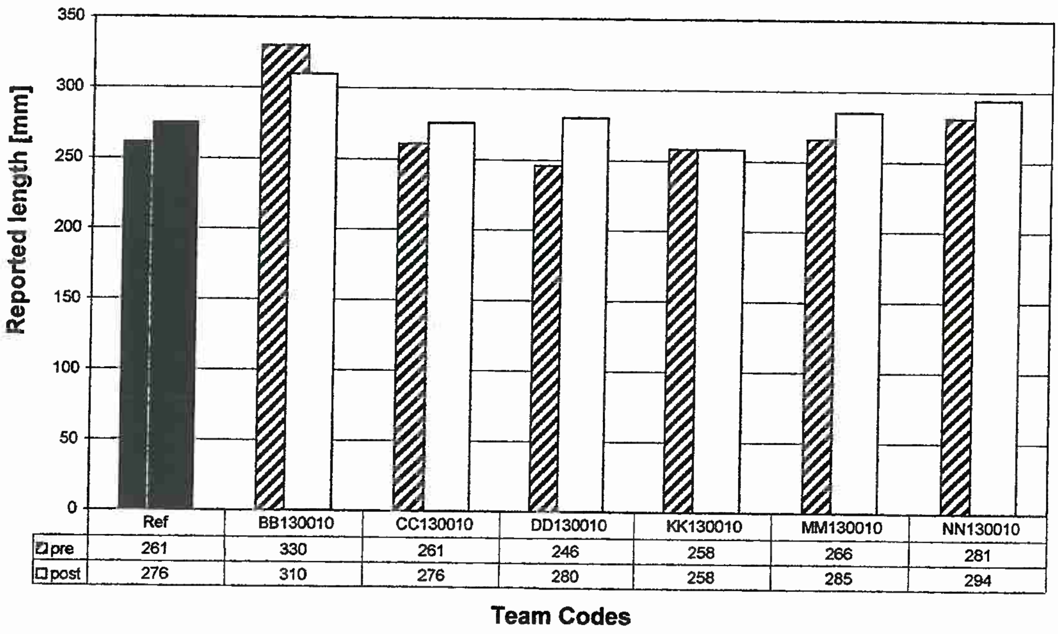
Figure 40 Difference in pre- and post-test TWE measured for defect B

Two teams (BB, DD) indicated a relatively large difference in the pre-test and post-test size of the through-wall extent of defect B. However, they both undersized defect B significantly in the pre-test inspection, so the larger values in Figure 40 for these teams mainly indicates improvements in their measurements, rather than a measurement of a large crack growth.

12.2 Crack growth in length

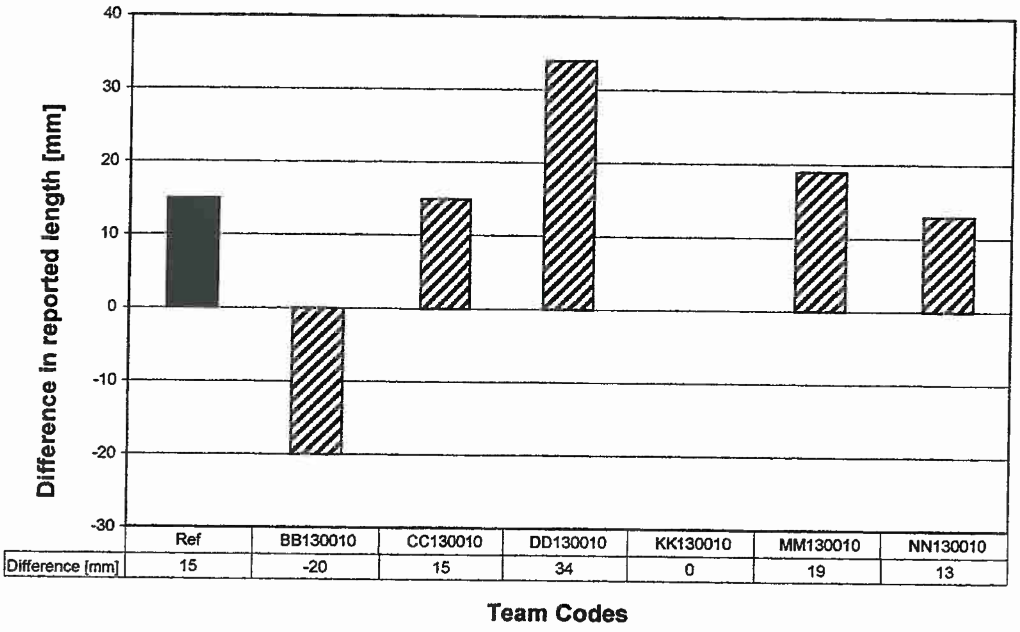
Defect B grew by 15 mm in length during the spinning cylinder test. In Figure 41 the pre- and post-test length, as measured by the different teams participating in the pre- and post-test inspection is represented. Two out of 6 teams (CC, MM) were capable of measure relatively accurately (within 10 mm) the length of defect B. These two teams measured a growth in length of 15 and 19 mm, respectively. Note, in this respect the dimensions measured by team CC, which are exact up to the mm.

In Figure 42 the difference between the pre-and post-test length is shown as measured by the different teams that participated both in the pre-test and post-test RRT is shown. Note, team NN also relatively accurately measured the crack growth length (13 mm). However, they oversized defect B in both the pre-test and the post-test inspections with by about 20 mm.



	Ref	BB130010	CC130010	DD130010	KK130010	MM130010	NN130010
▨ pre	261	330	261	246	258	266	281
☐ post	276	310	276	280	258	285	294

Figure 41 Comparison of pre- and post-test length sizing of defect B as measured by the teams who participated in the pre- and post-test inspections.



	Ref	BB130010	CC130010	DD130010	KK130010	MM130010	NN130010
Difference [mm]	15	-20	15	34	0	19	13

Figure 42 Difference in pre- and post-test lengths measured for defect B.

13 PROFILING OF THE LARGER DEFECTS

The teams were asked to profiles the two larger defects, although this request was not mandatory. Five teams provided profiles of the large sub-clad fatigue crack (Defect B) at the pre-test inspection stage and eight gave profiles of both defects at the post-test stage. The measured profiles of the larger defects B and RL are compared with the ones obtained by destructive examination in appendix 13, part II.

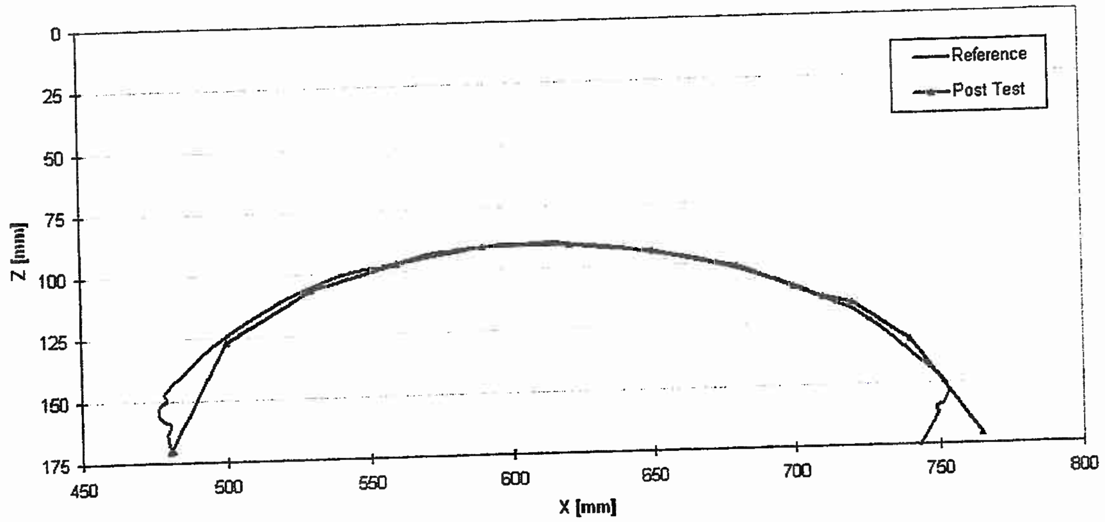


Figure 43 Profile reported for Defect B by a typically in the post-test inspection together with the reference profile determined by destructive examination.

In general, the results were good and conformed to the profile of the cracks in the deeper regions. An example of the results typically obtained by the teams is shown in Figure 43 together with the profile determined by destructive examination.
However, the profiling achieved by one team, using the focussed probe technique, was outstanding and accurately followed the lobes on the two cracks. This team was capable of determining accurately the profile of the 2 defects with the lobes present at both ends. The profiles of defect B reported by team CC in the pre-test and the post-test, respectively, are shown in Figure 44 and Figure 45 Please note that this team was able to determine the lobes at the end of the defect, which occurred during the spinning test.

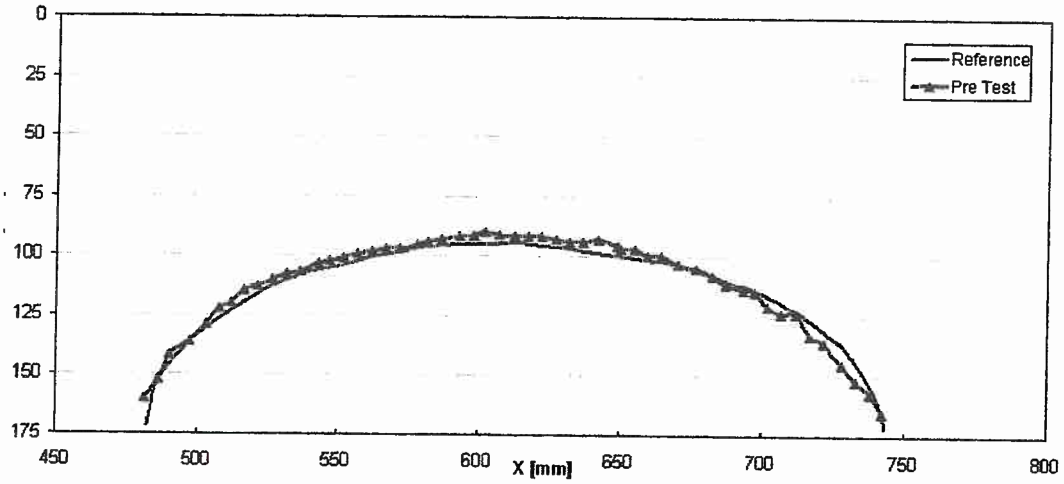


Figure 44 Profile reported for Defect B by team CC in the pre-test inspection together with the reference profile determined by destructive examination.

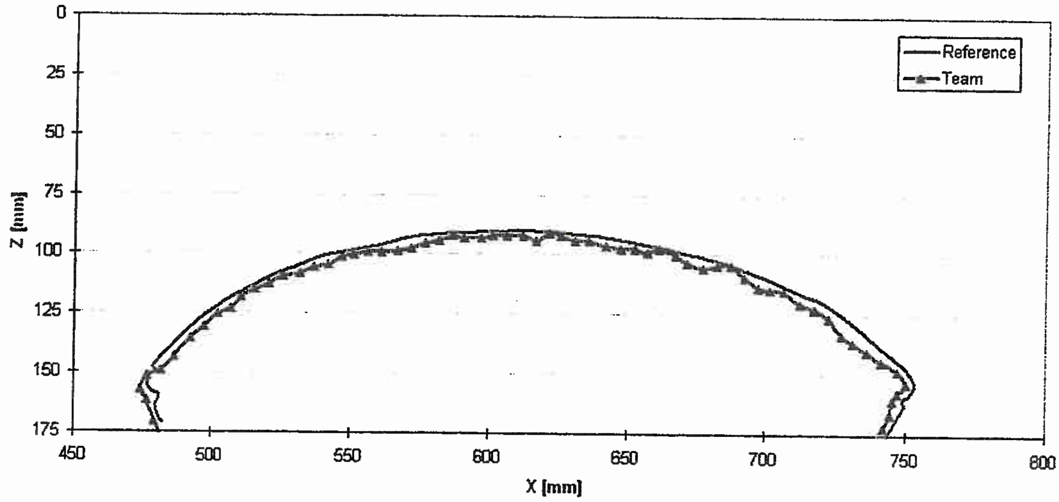


Figure 45 Profile reported for Defect B by team CC in the post-test inspection together with the reference profile determined by destructive examination.

14 EVALUATION OF THE INFLUENCE OF TECHNIQUES

14.1 Overview of the Techniques Used

In Table 19 the inspection techniques used by the different teams are summarised. This has been constructed in a manner that does not divulge the actual identity of the teams taking part in the inspections. More details can be found in Appendix 14.

14.1 Influence of inside/outside inspection and number of techniques used on the detection performance

The detection rates achieved by the different inspection teams, classified according to the number of different techniques used and the side from which they were applied (inside, outside or combed inside/outside) are represented in Figure 46 and Figure 47 for the pre- and post-test inspections respectively; only the techniques used for detection are included.

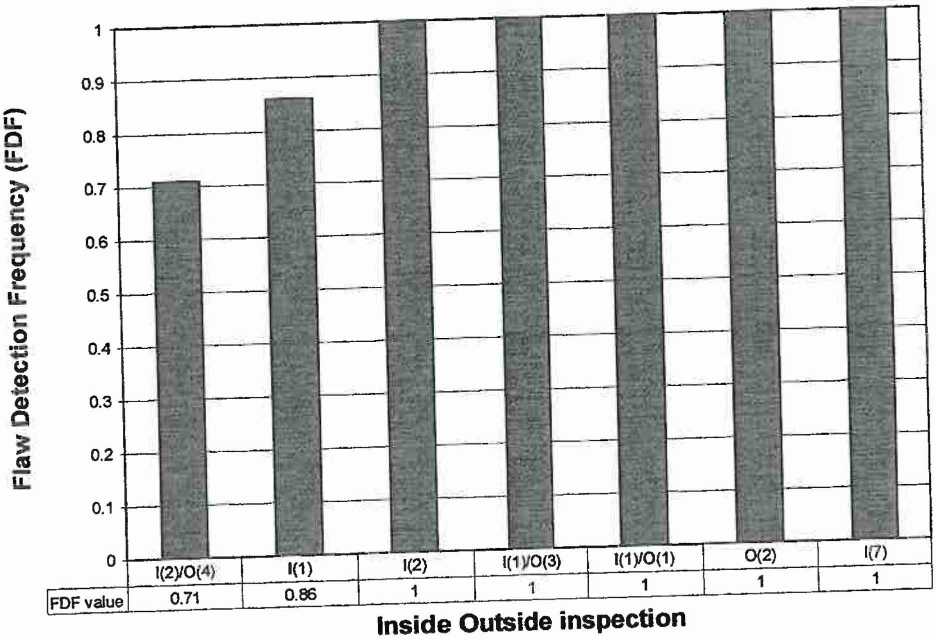
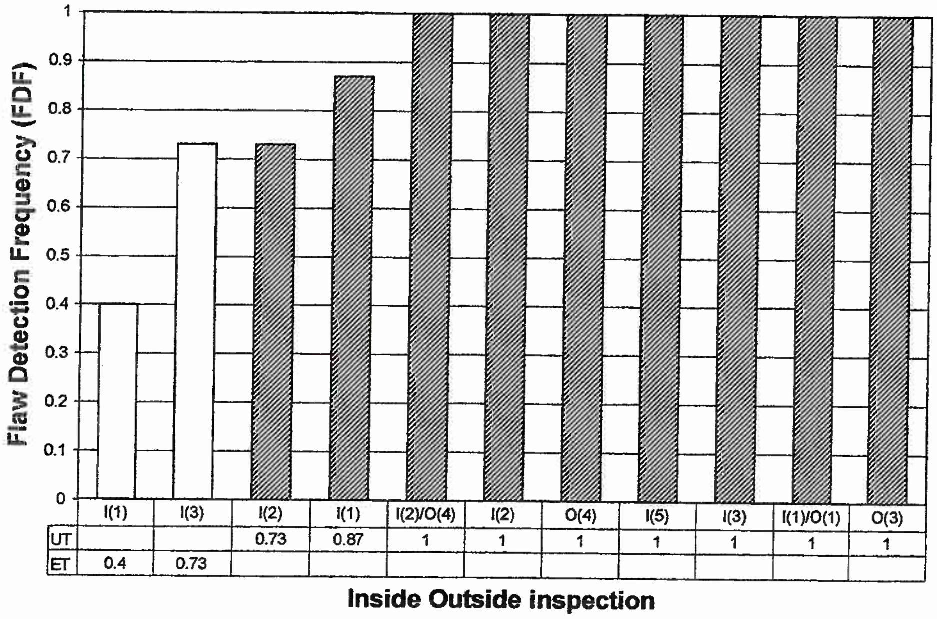


Figure 46 Detection Frequency for pre-test inspection teams showing the number of inside/outside detection techniques used.

In the pre-test inspections, three teams inspected the cylinder only from the inner surface, one team inspected only from the outer surface, and three teams performed a combined inside/outside inspection. The number of techniques used for detection varied from 1 to 7 and this is shown in parenthesis in the Figure. The results show that of the teams achieving 100%

detection, one used 2 techniques from the inner surface, one used 2 technique from the outer surface, and one used 1 technique from the inside and 1 from the outside.
The Figure also shows that one team used 7 techniques from the inner surface and another used only 2, and yet both achieved 100% detection. This indicates that the inspection surface has no significant effect on detection performance, although the influence of the cladding parameters needs to be considered separately; this is discussed below.

In the post-test inspections (Figure 47), seven teams inspected from the inner surface, two inspected from the outside, and two performed a combined inside/outside inspection. The number of different techniques varied from 1 to 5, and here, as with the pre-test inspections, there is no significant effect of inspection surface or the number of techniques used.



	I(1)	I(3)	I(2)	I(1)	I(2)/O(4)	I(2)	O(4)	I(5)	I(3)	I(1)/O(1)	O(3)
UT			0.73	0.87	1	1	1	1	1	1	1
ET	0.4	0.73									

Figure 47 Detection Frequency for post-test inspection teams showing the number of inside/outside detection techniques used.

From these results, it is concluded that there is no correlation between detection rate and the number of techniques used or the surface from which the scanning was performed. The later conclusion may have been influenced by the condition of the cladding on the NESC 1 cylinder.

DETECTION					LENGTH SIZING	TWE SIZING	GENERAL		
Scan. side of cylinder	Technique used for detection [a]	Frequencies used for detection [MHz]	Angles used for detection [°]	Detection Level	Main technique Length Sizing	Main technique TWE sizing	Inspection(s) performed by team	Scanning type used by team	Comment
Inside & Outside	SC-Sh(2), SC-Lo(1), DC-Lo(1), Creeping wave(1)	1.8 2.5	0, 40, 50, "90"	FBH = (A = 5 mm2)	Recording level & 6 dB drop	Amplitude & PE Crack Tip PE [0 deg]	Pre-test & Post-test	Manual	
Inside	SC-Lo(1) [focussing probe]	5	55	Noise level	6 dB drop	PE Crack Tip	Pre-test & Post-test	Automatic	
Inside	Phased array (Long = 8, Shear = 6), DC-Lo(1)	1.3 2.0	35 - 70, 70	a) 25% DAC SDH ø3mm b) 10 mm slot + 6 dB	6 dB drop	Amplitude & PE Crack Tip PE Crack Tip (Ph. Ar.)	Pre-test & Post-test	Automatic	
Inside	SC-Sh(2),	1.0 2.0	45	Noise level	6 dB drop + Conturing	PE Crack Tip (SAFT)	Post-test	Automatic	This team did not inspect the whole cylinder
Outside	SC-Sh(2), SC-Lo(2)	1.0 2.0	28, 30, 35, 39	Noise level	6 dB drop	TOFD & PE Crack Tip Crack Tip (Ph. Ar.) PE [0 deg]	Post-test	Automatic	
Inside	SC-Sh(1), DC-Lo(1), DC-Sh(1), Tandem-Technique(2)	1.0 2.0	45, 70	NESC D 7x51 mm slot + 13/15 dB	6 dB drop	PE Crack Tip	Post-test	Automatic	
Inside	Low frequency ET(2), Standard ET(1)	0.5/2.8/5.0 kHz 50/280/600 kHz	-	NESC ET Calibration Blocks	-	-	Post-test	Automatic	
Inside	SC-Sh(1), DC-Lo(1), Creeping wave(1)	2.0 2.5	45, 70, "90"	Noise level	6 dB drop	TOFD & PE Crack Tip	Post-test	Automatic	
Inside & Outside	SC-Sh(2), DC-Lo(1), TOFD(4)	1.0, 2.0 2.25, 5.0	38, 45, 70, 35, 45	25% DAC SDH ø8 mm, & NESC A,B,C slots	6 dB drop	TOFD & PE [0 deg]	Pre-test & Post-test	Automatic	
Inside & Outside	SC-Sh(1), DC-Lo(1)	2.0 3.5	45, 70	Thermal Fatigue cracks in block B-2289-1-1000	Loss of signal	PE Crack Tip (SAFT)	Pre-test & Post-test	Manual & Automatic	
Outside	SC-Sh(3)	1.5	22, 31, 41	Noise level	Loss of signal	PE Crack Tip (SAFT) PE [0 deg]	Pre-test & Post-test	Automatic	
Inside	Standard ET(1)	40/50/75/100 kHz	-	NESC Eddy Current Calibration Blocks	-	-	Post-test	Automatic	
Inside	SC-Sh(3), SC-Lo(2), DC-Lo(2)	2.0 4.0	0, 45, 60, 70	10% DAC, SDH ø8 mm + 4 dB	6 dB drop	TOFD & PE Crack Tip	Pre-test	Automatic	

[a] SC-Sh : Single Crystal Pulse Echo in Shear Wave Mode
SC-Lo : Single Crystal Pulse Echo in Longitudinal Wave Mode
DC-Sh : Dual Crystal Pulse Echo in Shear Wave Mode
DC-Lo : Dual Crystal Pulse Echo in Longitudinal Wave Mode

Additional two teams (not shown in this table) performed only additional length and depth sizing of inspection data recorded by a team in this table

Table 19 Overview of the inspection techniques used by the different inspection teams.

14.2 Influence of type of TWE sizing technique used

To examine the influence of the techniques used sizing the through-wall extent of the defects the teams have been classified according to the techniques they employed. This can be summarised as follows

a)	TOFD:	Using Time Of Flight Diffraction techniques
b)	Crack Tip (Conventional PE):	Using crack tip diffraction on data recorded with conventional pulse echo probes
c)	Crack Tip (PE SAFT):	Using crack tip diffraction after applying a SAFT- algorithm on data recorded with conventional pulse echo probes
d)	Crack Tip (PE Focus):	Using crack tip diffraction on data recorded with focussing probes
e)	Crack Tip (Phased Array):	Using crack tip diffraction on data recorded with phased array probes
f)	Crack Tip (Tandem):	Using crack tip diffraction on data recorded in a tandem configuration with conventional pulse echo probes
g)	PE (0°)	Using 0 degrees pulse echo probes.
h)	Amplitude based	Using any amplitude based sizing method with any kind of recorded inspection data

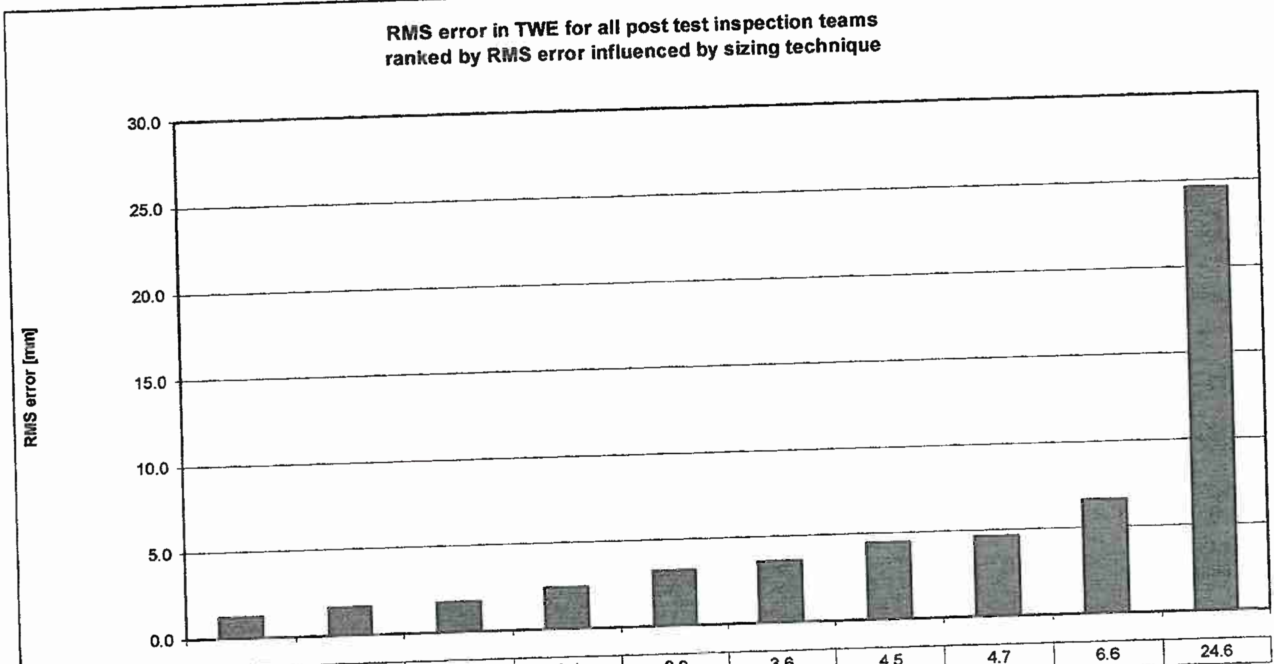
In Figure 48 the RMS error is plotted for the different inspection teams which are classified according to the type of TWE sizing technique used:

The four teams, which performed best in TWE sizing, with and RMS error of 2.4 mm or less, all utilised the tip-diffracted wave from the crack tip to size the defects, however they used different techniques to obtain the crack tip signal. The techniques used are listed below.

1. TOFD
2. Crack Tip (PE SAFT)
3. Crack Tip (PE Focus)
4. Crack Tip (Conventional PE)

This result is very important in that it indicates that for good sizing of the through-wall extent of defects it is necessary to base the sizing technique on the tip-diffracted wave from the defect. On the basis of the evidence obtained in the present studies it appears that the specific technique used to obtain the crack tip signal is not influential.

However all the teams used a form of technique based on the crack tip signal and yet they did not perform equally well, thus it highlights the need for inspection qualification of both the inspection system and the personnel.



RMS error [mm]	1.2	1.6	1.8	2.4	3.2	3.6	4.5	4.7	6.6	24.6

Sizing Technique

TWE sizing technique No 1	TOFD	Crack tip (PE SAFT)	Crack tip (PE FOCUS)	Crack tip (PE SAFT)	Crack tip (PE CLASSIC)	Crack tip (PE SAFT)	Crack tip (PE CLASSIC)	Crack tip/Ampl (PE CLASSIC)	TOFD	Crack tip/Ampl (Phased. Array)
TWE sizing technique No 2	Pulse Echo (0°)			Crack tip (PE CLASSIC)	TOFD	Crack tip (PE CLASSIC)	Crack tip (TANDEM)	Pulse Echo (0°)	Crack tip (PE CLASSIC)	Crack tip/Ampl (PE CLASSIC)
TWE sizing technique No 3				Pulse Echo (0°)	Crack tip (Phased. Array)					
TWE sizing technique No 4					Pulse Echo (0°)					

Figure 48 RMS error for the post-test inspection teams classified according to the type of TWE sizing technique used

14.4 Influence of inside/outside inspection and number of techniques used on the TWE sizing performance

The RMS error for the post-test inspections, classified according to the number of inside/outside TWE sizing techniques used, is shown in Figure 49.

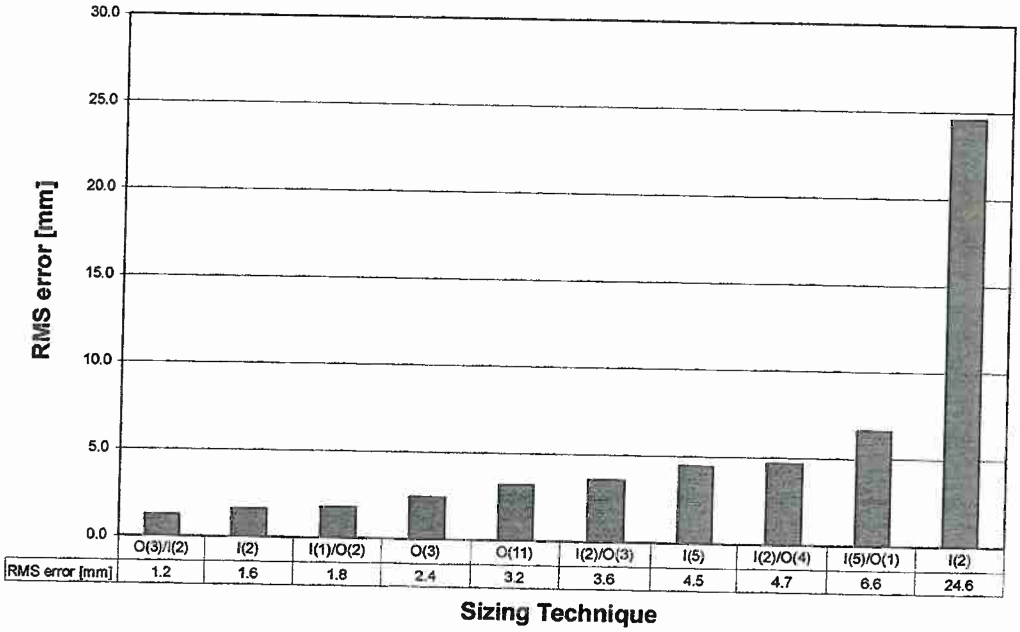


Figure 49 RMS error in TWE sizing for the post-test inspections classified according to the number of inside/outside sizing techniques used.

From these data, it is concluded that the number of techniques does not appear to exert a significant influence on the TWE sizing. With respect to the influence of inspection surface on sizing accuracy, there is insufficient data available in the present study to draw conclusions. This is a factor that could be included in any further study of performance influencing parameters.

14.5 Influence of inside/outside inspection and number of techniques used on the length sizing performance

The RMS error for length sizing for the post-test inspection teams is shown in Figure 50, together with the number of techniques used from the inner and outer surfaces of the cylinder. From the figure it is clear that the number of length sizing techniques is not significant in defining the accuracy of length sizing. From detailed analysis it appears that most of the better teams included a 70 degrees TRL probe from the inner surface amongst the techniques used.

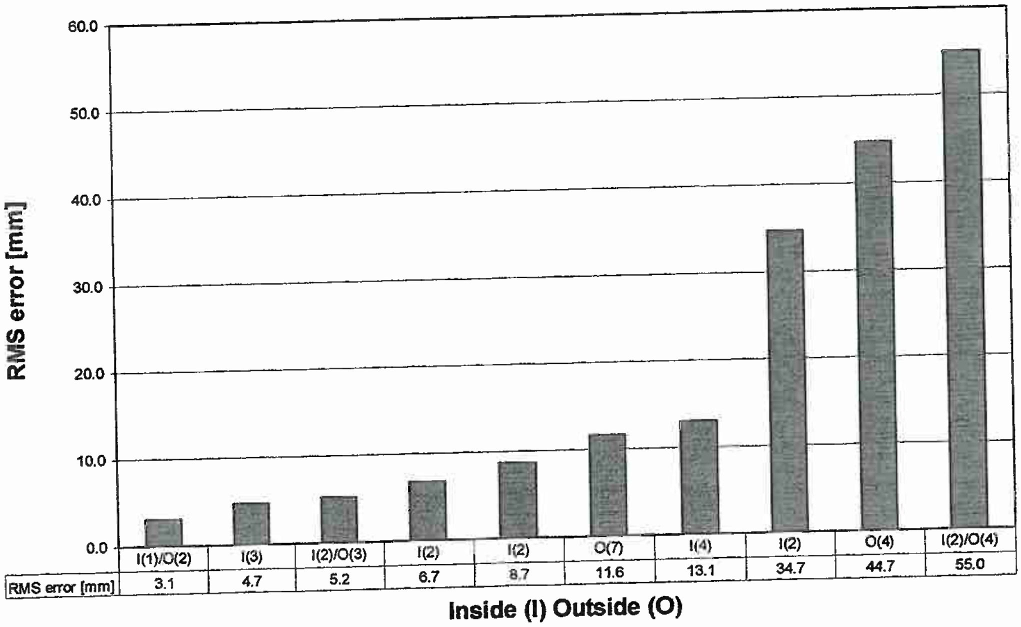


Figure 50 RMS error in length sizing for the post-test inspections classified according to the number of inside/outside sizing techniques used.

15 INFLUENCE OF DEFECT CHARACTERISTICS ON DETECTION PERFORMANCE

The flaw detection rate (FDR) achieved in the pre-test inspections are shown in Figure 51 as a function of defect through-wall size for the three categories of defect in the cylinder, namely, large planar defects, sharp-tipped EDM notches and realistic underclad cracking.

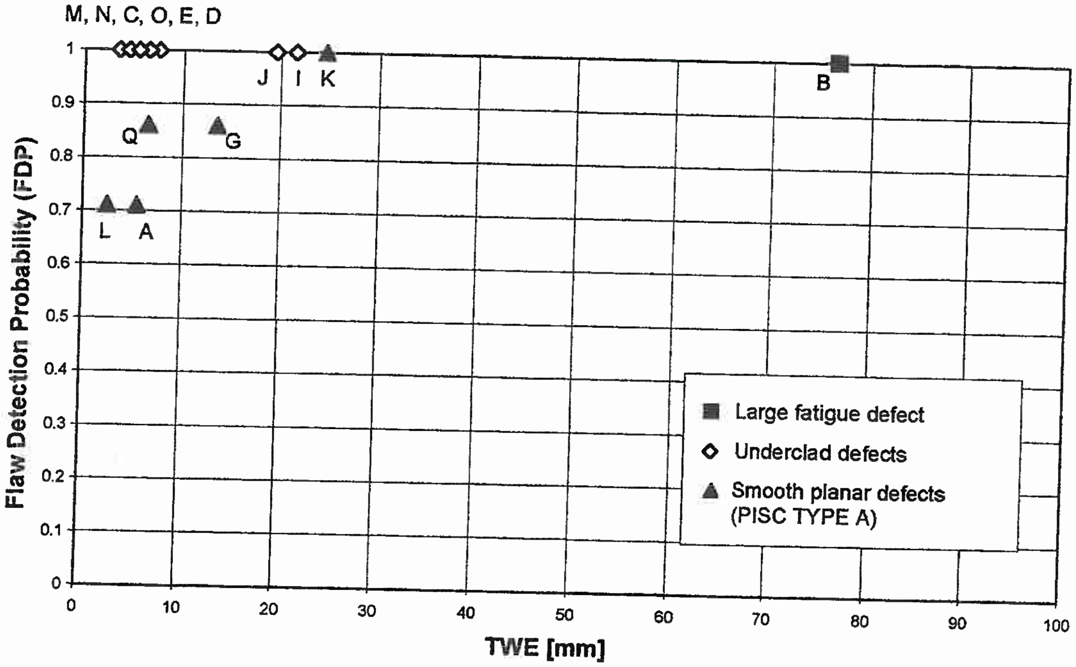


Figure 51 Flaw Detection Probability as a function of the TWE in the pre-test inspections

The realistic underclad cracks were detected by all teams. The EDM notches A and L were detected by 5 of the 7 teams, and EDM notches Q and G by 6 of the teams. This indicates that in the present studies the EDM notches were more difficult to detect than the realistic underclad cracks. The good detection performance of the later category of defect may possibly be due to the presence of small cracks perpendicular to the main crack (see table 3). The morphologies of the defects are described in detail in the Destructive Examination Report[6]. It is not possible to clarify the extent to which the presence of porosity in the cladding close to the defects has influenced detection performance.

16 SUMMARISING DISCUSSION

Six evaluation tasks were defined by TG1 to ensure that the objectives specified for the inspection group were achieved, and these are outlined in Section 3.2, which describes the objectives of the task group. In this summarising discussion, the sequence follows that given to the evaluation tasks. The two final sections deal with, respectively, the sensitivity analysis performed collaboratively with TG2 and TG3, and with the factors to be considered in extending the conclusions and recommendations into practice in in-service inspections.

16.1 Discussion of Inspection Performance

Summarising briefly, seven teams participated in the pre-test inspections using ultrasonic techniques and ten in the post-test inspections; two more teams inspected the cylinder post-test using eddy current techniques. Most of the teams used ultrasonic techniques routinely employed in the ISI of nuclear pressure vessels.

Detection performance was generally good with five of the seven teams detecting all the defects in the pre-test inspections and eight out of ten in the post-test inspections. One of the two teams not achieving 100% detection was the same in both phases. The other teams missing defects were different in the two phases of the inspections. One team, using manual techniques, missed a group of four underclad cracks pre-test but detected them post-test. It was reported that this team had received training in the period between the inspections and that an additional inspector had joined the team for the post-test phase, and it is considered that this may have contributed to the improvement in performance. The other team, using automatic scanning, reported a group of underclad cracks in the first inspection but missed them in the second. Since the same staff, equipment and procedures were used in both phases of the inspections this suggests that a human error was made in either setting up the equipment, scanning or interpreting the signals obtained.

The ultrasonic techniques used for detection ranged from: pulse echo using single crystal and twin crystal probes in either shear wave mode or longitudinal mode; focussed probes; phased arrays; tandem; SAFT and TOFD. The detection threshold ranged from noise level to a 20 mm^2 FBH. When the results are examined in terms of the techniques employed by all the teams there is no evidence that the detection procedure or techniques used exerted a significant influence on detection capability. Indeed, the observation that non-detections occurring in the first phase were rectified in the second by one team, and conversely that another team missed defects in the second phase that it had found in the first indicates that the techniques employed were inherently capable of detecting the defects and that the failure to do so was due to some other cause, probably human error in setting up the equipment, scanning or interpreting the data obtained.

The detection performance of the two teams using eddy current techniques was not as good as for teams using ultrasonic techniques, one detecting only 6 out of 15 defects and the other 11 out of 15. It must be recognised that the defects in the NESC 1 cylinder were not entirely suitable for eddy current techniques. This was discussed in detail in 9.1.

In the pre-test inspections the accuracy of 4 of the 7 teams in sizing the through-wall extent of the defects was very good with a mean error of 2 mm or less and a standard deviation for four of them of less than ±3 mm. The corresponding RMS error for these 4 teams was 3.4 mm or less. The fifth team had also had a good mean error result of 0.1 mm, but a standard deviation of ±7.6 mm. The two remaining teams however showed significant undersizing of most of the defects in their pre-test inspections, including in particular the large sub-clad fatigue crack.

In the post-test inspections four teams sized very accurately with a mean error of less than 1 mm and a standard deviation of ±2.5 mm or less. Five other teams achieved a similar mean error with a standard deviation better than ±7 mm. The remaining team, as in their pre-test inspection, showed significant undersizing and a large standard deviation.

The individual through wall extent sizing results for each team are shown in appendices 5 and 7 for the pre-test and post-test inspections, respectively. Two of the good teams, CC and KK, achieved sizing accuracies of sizing of the defects in both inspections that could hardly be bettered, as did team EE in the post-test inspection.

The accuracy of sizing the crack growth that occurred as a result of the spin-test on the cylinder varied. Of the teams that submitted relevant data, two were very accurate, with measurements within 0.5 mm of the actual growth of 5 mm, two teams were within 6 mm and the two remaining teams made significant errors.

As part of the reporting procedure, teams were asked to determine, if possible, the profile of the large defects, although this request was not mandatory. Destructive examination of the cylinder after the final inspections showed clearly that during the spin test both of the large defects grew, mainly in the axial direction just below the cladding/base metal interface, giving lobes at both ends of the sub-clad fatigue crack (Defect B), and one lobe at the end of the through-clad defect (Defect RL). The task of obtaining a signal from around the complete curvature of the lobes is not favourable to most of the techniques when used in a normal manner and the profiling of such lobes is a demanding task. Nevertheless, five teams provided profiles of the large sub-clad fatigue crack at the pre-test stage and eight gave profiles of both large defects at the post-test stage which in general were good and conformed to the profile of the cracks in the deeper regions. However, the profiling achieved by one team in the post-test inspections was outstanding and accurately followed the contours of the lobes on the two cracks. This technique was based on the use of the focussed probe technique.

16.2 Factors Influencing Performance

In discussing some of the factors, which may have exerted an influence on the inspection performances, it is to be noted that there were some aspects of the trials which differed from the inspection conditions normally encountered on-site. These will be discussed in section 16.7 below, first, the factors leading to good performance in sizing will be summarised.

For sizing the through-wall extent of a defect, the NESC results have shown the importance of using the tip-diffracted wave from a crack tip. Teams using this technique in general sized defects well, and it appears that the specific method employed to obtain this type of signal is not influential. Conventional pulse echo, or techniques using pulse echo signals, or techniques designed specifically to obtain the crack tip signals all performed well. To some extent the variability in sizing accuracy appears to stem from the operator rather than the technique used. The same comment applies to length sizing for which all the teams used amplitude drop techniques.

As noted above, there were some aspects of the trials which differed from the inspections conditions normally encountered on-site, and the possible influence of these aspects on the results need to be considered. Firstly, access to the cylinder was more favourable than might be the case during an ISI on-site, since the inspections were performed under laboratory-type conditions with easy access to both surfaces of the cylinder. With respect to the influence of inspection surface on sizing accuracy, there is insufficient data available in the present study to draw conclusions. This is a factor that could be included in any further study of performance influencing parameters. However, the influence of the type of cladding used on the NESC cylinder on the results also needs to be considered and this is discussed below.
A second potentially beneficial factor was the length of time allowed for the inspections; this was two weeks. However, from information supplied by the teams after the inspections it appears that many of the teams experienced time pressure in completing the sizing of the indications detected due to the relatively large number of defects present in the cylinder. In view of this the DAG concluded that the length of time allocated was not a particularly beneficial factor.

Another factor that could have had a beneficial effect on performance relates to the thickness and surface condition of the cladding. In the present studies the cladding was 2-layer strip cladding machined down to a thickness of 4 mm in order to increase the probability of crack growth occurring during the spin test on the cylinder. In practical situations in the field this type of cladding is often 7 to 11 mm thick and may not have a smooth machined finish. Previous studies of the influence of cladding carried out by AEA Technology[7] and later as part of the PISC II Parametric Studies[8] found that the surface finish associated with a strip-clad surface could have a profound effect on the amplitude of the ultrasonic beam entering the component. Amplitude was found to vary by up to 20 dB to 25 dB for a surface roughness (error of form) of the order of 1.5 mm per 50 mm for the as-clad finish. The PISC studies also showed that due to splitting or smearing of the beam it was possible for the position of a FBH to be mislocated for some conditions.

Cladding thickness was also found to affect shear wave transducers and to a lesser extent those employing longitudinal waves. The effect was, however, smaller than that of surface finish. It is probable that the difference between the thickness found more usually in practice and that used in the present studies can be considered a relatively minor influence. For 2 MHz shear waves contact probes, small amplitude variability persisted even when the cladding was machined down to the interface between the austenitic cladding and the ferritic base metal. This interface undulates along its length due to different levels of penetration occurring when laying down the first layer of cladding, and the localised curvature can cause changes in beam angle and beam focussing or de-focussing. However, this effect was present in the NESC inspections.

Clearly the influence of surface finish was absent from the NESC inspections, which in general used a combination of transducers from the range discussed above, some of which might have been affected by an as-clad surface finish, and so the NESC results, strictly, will apply to inspections in which the surface is relatively smooth. It is considered, therefore, that the NESC inspection results should be regarded as a benchmark for the capability of present inspection technology, which is not a function of a specific cladding condition.

It is recommended that when selecting techniques for practical ISI applications, the parameters of the actual cladding should be taken into account when specifying the transducer parameters. With optimum probe parameters it should be possible to reduce significantly the influence of cladding. It is also recommended that the effectiveness of inspection procedures for a specific inspection involving cladding should be verified by inspection qualification methodologies using test specimens with relevant cladding.

A factor that, potentially, could have had a deleterious effect on performance was the size of the two large defects inserted in the cylinder. However, the teams were advised at the outset that the range extended from realistic underclad cracks to large fatigue cracks. Furthermore, detection and sizing was generally good over the entire size range, and where errors were made other causes were identified to explain their occurrence. It is considered therefore, that this factor did not have a significant effect on the results achieved.

The effect of the number of probes, i.e., techniques, used by a team has been evaluated, since a larger number of probes gives, in principle, more chances of obtaining a signal. However, examination of the results indicates that there is no significant difference in performance between teams using one or two techniques and those using up to five or seven. Similarly, the spacing of the scan raster could, in principle, influence detection capability by giving more chances of obtaining a signal from a defect. In the present tests most teams used a smaller raster than would generally be expected for on-site inspection, although one team scanned with a 10 mm raster. Since the latter team also detected all the defects it is considered that the spacing of the scanning raster was not significant in the present studies. For sizing, it is common practice for inspectors to use small raster scans, so the sizing procedures used in the present tests probably conform more to practice.

16.3 Influence of Human Error

Mistakes were made in both sizing and detection that could be attributed to the inspection teams. In one case, a team did not report defects, which were actually present in the data, because they were considered to be too small. This is unlikely to be due to the capability of the techniques used since other similarly sized defects were reported. In another instance, a team failed to detect defects in the post-test inspections which had been reported in the pre-test inspections. It is postulated that this may have been due to incorrect application of the scanning procedures, since adjustment had to be made to the defect locations reported in the pre-test data because of apparent scanning errors. Another team detected defects in the post-test inspections, which it had missed in the first phase. The Reference Laboratory was informed that this team had received some training between the inspection phases and that an additional inspector had joined the team for the second phase and it is considered probable that this contributed to the team's improved performance.

The teams that sized the through-wall extent of defects accurately used sizing techniques based on crack tip signal and yet they did not perform equally well, this highlights the need for inspection qualification of both the inspection system and the personnel.

There are other factors that can be encountered during an on-site inspection that could contribute to the incidence of human error, which were not studied in the NESC inspections. These include long working hours and shift work causing inspector tiredness, pressure of management to complete the inspections within a given time, concern about radioactive conditions, and the tedium associated with repetitive work.

This range of errors can be controlled, to some extent, by the use of unambiguous inspection procedures, well-designed equipment, adequately trained inspectors, preferably having been trained for the specific application, and good supervision during the actual inspection. Many of these aspects are covered by preparing for, and taking part in, inspection qualification exercises, but others, such as on-site supervision, need specific consideration when planning an on-site inspection.

16.4 Best Inspection Practices

The results show that the majority of the teams achieved good detection results using high sensitivity at the search stage. This was also a conclusion reached in the PISC exercise. This is therefore a recommendation on best inspection practices for good detection. It is recognised that some development studies will normally be required to set an appropriate threshold, probably close to the level of ultrasonic noise, but this will ensure that the best possible detection capability is achieved.

The sizing data indicate that good accuracy in sizing the through-wall dimension of the defects is achieved by techniques based on obtaining and analysing signals from the crack tip. Most of the teams employing this method achieved good sizing results, and this therefore is a recommendation on best sizing practice. However, there was some variability in the sizing results and it appears that reliable sizing performance is a function both of the use of the tip-diffracted wave and of the inspector's capability. Adequate qualifications and proper training in applying the techniques to typical defects is also a strong requirement.

In sizing the length of the defects, teams performed satisfactorily using amplitude drop techniques but care is needed in specifying this technique for application in practice since the relative size of the defect and the width of the insonifying beam must be taken into consideration when specifying the technique to be used.

Most of the teams that provided profiling data on the two large defect showed a capability to contour most of the leading edge of the defects. The results stem from the capability of techniques based on using the tip-diffracted waves to obtain relevant information and of advanced data analysis and display systems to provide a contour of most of the edge of a defect. One team however, also provided a profile of the lobes that grew at the ends of the defects during the spin test on the cylinder. This technique is based on the use of focussed probes. Normally, in practice, crack profiling is not something that is requested in ISI, but where it is required application of the focussed probe technique is recommended.

16.5 Suitability of the Defects for ISI Qualification

There are several factors to be considered when assessing the suitability of various defect types for insertion in ISI qualification test assemblies. Principally, they must be representative ultrasonically of the type of damage to be detected, but as well it must be possible to define accurately the size and position of the test defects. This later task is usually must easier for artificial type defects than for realistic defects, for which destructive examination is usually required. Since destructive examination destroys the test assembly considerable expense can be involved, both in carrying out the destructive examination and, if necessary, replacing the test assembly. Another important consideration is that when an artificial-type defect is inserted in a test assembly the surrounding material is not disturbed by the fabrication process. In considering whether to insert artificial or realistic defects one of the main questions to be addressed is whether the artificial defects presents broadly the same level of difficulty to the detection and sizing techniques included in the inspection procedures.

In the present study, the artificial sub-clad EDM notches proved to be somewhat more difficult to detect than the realistic hot or cold cracking. Possibly the main difference between the defects types was that the EDM notches were smooth-sided whereas the realistic cracking had some roughness on the crack surfaces and, in some cases, even facets. This would tend to improve the detectability of the realistic cracking, although the results suggest that this was not a major influence.

In addition, the EDM notches inserted in the NESC cylinder had been fabricated with sharp radius tips making the ultrasonic response of the crack tip similar to that of the realistic cracking. This factor made the sizing task of similar difficulty.

It is concluded therefore that the sharp radius EDM notches could be considered as suitable for use in ISI qualification test assemblies, provided that they adequately represent the damage to be detected and that the challenge to the detection and sizing techniques is of similar difficulty. However, the porosity occurring at the intersection of the crack tip with the cladding interface is something that should be avoided.

The large fatigue cracks used in the NESC cylinder are larger than would be expected in practice and therefore would not normally be considered for use in inspection qualification exercises.

The analysis of the NESC inspection data has confirmed the necessity of verifying in detail the parameters of the defects used in test assemblies.

16.6 Sensitivity of Structural Analysis to Variability in Sizing Accuracy

One of the objectives of the NESC 1 project as a whole was to assess the sensitivity of the predictions regarding the stability of the defects in the NESC cylinder during the pressurised thermal shock test to variability in the inspection and materials property data supplied by the respective Task Groups to the structural integrity analysts. To this end, a sensitivity analysis has been performed[2], which aimed to demonstrate how different input data in the fracture assessments would influence the assessment results. The study covered a range of input parameters, especially the crack driving force and the time for the eventual cleavage event, and included an assessment of the effect of crack size on the time to a cleavage event.

One of the cases examined in the study looked at the effect of the size of the through-clad crack, assuming it to be initially 73 mm deep and 205 mm long and then 80 mm deep; other input parameters remained unchanged. It was found that the deeper crack caused a higher crack driving force, J, in the cladding HAZ but lower at the deepest point of the crack front. A larger part of the crack front of the smaller crack was under compressive thermal stresses during the transient. According to the analysis, a 10% increase in crack depth resulted in about 5% increase in the J-value in the cladding HAZ. This implies that, for this case, the crack driving forces are not very sensitive to the crack depth.

A second part of the study looked at four sub-clad elliptical cracks with depths ranging from 7 mm to 84 mm. For each defect geometry three different crack depths and three different RT_{NDT} (Reference Temperature-Nil Ductile Transition) values were studied. The results can be summarised from an inspection point of view by plotting the predicted time to cleavage versus the depth of the crack tip; this is shown in Figure 52 for two of the RT_{NDT} values studied. This indicates that for large sub-clad defects with a depth greater than, say, 30 mm or 40 mm the time to cleavage increases linearly with crack tip depth. For small crack sizes below, say, 7 mm, it appears that the time to cleavage is not greatly affected by crack size.

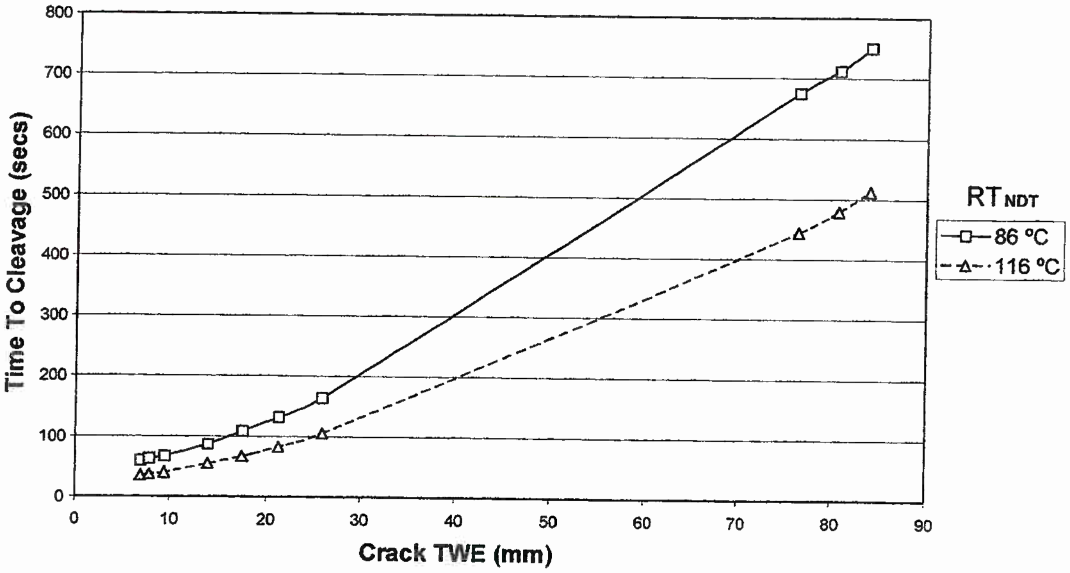


Figure 52 Effect of crack tip depth on time to cleavage.

This raises an interesting aspect for inspection, namely that in the case of the NESC 1 cylinder test the accuracy of sizing small underclad defects does not greatly influence the time to cleavage. For large defects, an undersizing error of 10 mm on a 70 mm defect reduces the time to cleavage from 600 seconds to 500 seconds. The results of the sensitivity study, which may be specific to the NESC 1 conditions, suggest that the defect sizing accuracy demonstrated in the NESC project may be more than adequate for the purposes of analysing the structural integrity of a structure.

16.7 Extension of the Results into Practice

The NESC inspection programme has indicated the techniques, which possess a high capability to reliably detect and accurately size defects. However, a good capability in the present exercise does not necessarily imply that this will automatically result in reliable in-service inspection. Other factors exist that are related both to conditions on-site and to the inspector that can influence the effectiveness of an ISI. Notable amongst these are the qualifications and, particularly, the adequacy of the training of an inspector for the task in hand. These latter aspects, and the capability of the techniques specified for the inspection, can be tested and validated in an inspection qualification exercise, and it is a strong recommendation from the NESC programme that the capability of the inspection equipment, procedures and personnel planned for use in an ISI should be validated by inspection qualification methodologies.

The on-site factors that can militate during an ISI to reduce the effectiveness of the inspection include long working hours and shift work causing inspector tiredness, pressure of management to complete the inspections to time, concern about radioactive conditions, and the tedium associated with repetitive work. These were not studied in the NESC programme but some of them were examined in the PISC III programme[9]. From those studies it was concluded that the effectiveness of an inspector could vary significantly from day-to-day, particularly for manual inspectors, although the NESC and PISC results show clearly that human error can also occur in automated inspections. This range of errors can be controlled to some extent by the use of unambiguous inspection procedures, well-designed equipment, adequately trained inspectors, preferably having been trained for the specific application, and good supervision during the actual inspection. Many of these aspects are covered by preparing for and taking part in inspection qualification exercises, but others, such as on-site supervision, need specific planning when planning an ISI.

17 CONCLUSIONS

The following conclusions can be drawn from the results obtained from the programme of work carried out by the NESC 1 Inspection Task Group.

1. The prime objective of this international round robin inspection exercise to gather inspection information on the detection and sizing capability of a range of inspection techniques was successfully achieved.

2. The objectives of identifying some of the factors influencing the quality of inspection performance and indicating how procedures may be optimised have been achieved.

3. The accuracy of defect sizing achieved by the majority of the inspection teams enabled correct predictions of the growth behaviour of the defects in the cylinder during the spin-test to be made by the NESC Structural Integrity Group, TG3.

4. The detection performance achieved with ultrasonic techniques was good. Furthermore, the ultrasonic teams made no false calls in the pre-test inspections, and only one team made false calls in the post-test phase. This is the ideal performance from a reliability and cost-effectiveness point of view.

5. The detection results achieved with eddy current techniques were below the performances of the ultrasonic techniques. However, it must be recognised that the defects in the NESC 1 project were not entirely suitable for Eddy Current techniques. Furthermore, both the eddy current teams made some false calls, which possible could be explained by the fact that the Eddy Current techniques are capable of picking up small micro-structural changes in the materials.

6. Sizing of the through-wall extent and length of the defects was very good for the majority of the teams using several different techniques. It is considered that this was due firstly to the selection of optimum techniques for the purpose, secondly to the ability of the inspectors, and thirdly to the ability to control the occurrence of human error.

7. For sizing through-wall extent, techniques using the tip-diffracted wave of the defects were particularly effective, whilst for length sizing, amplitude drop methods were effective.

8. Most teams showed an ability to profile the deeper contours of the two large fatigue cracks; however, one team using focussed probes was capable of contouring the profile of the lobes at the ends of the defects.

9. The different number of techniques used by the different inspection teams was not found to be significant in defining inspection performance, and on limited information, it appears that scanning raster did not significantly influence detection performance.

10. In the study, the sharp-tipped, sub-clad EDM notches were found to be more difficult to detect than realistic hot or cold cracking. This indicates that EDM notches could be considered when designing test assemblies for inspection qualification testing.

11. The presence of porosities in the cladding above the EDM notches and the cold and hot cracking, most probably caused by the fabrication method, is something to be avoided. The presence of such porosities indicates the need to verify the defect fabrication methods used.

12. In general, the detection performances achieved in NESC 1 were better than the results obtained in PISC II, indicating that lessons have been learned from previous international exercises.

13. The studies show that human error must be controlled. This aim will be assisted by well-written unambiguous procedures both for data acquisition and data analysis, good quality control, training (including on-the-job training) and qualification of the inspection team. In addition, in-service inspection conditions should also be considered. Inspector motivation and the onset of tiredness are factors that can influence the effectiveness of inspectors, and the influence of other factors, such as long working hours, shift work, pressure of management, radioactive conditions, and tedium should all be considered when planning an in-service inspection.

14. The results indicate the importance of, and the need for, inspection qualification to verify and confirm that the entire inspection system, including the inspection procedure and personnel, is capable of meeting the inspection objectives defined at the outset. In cases where equipment and procedure are accepted by appropriate safety authorities, it may only be necessary for the inspectors to pass suitable personnel qualification examinations.
    The results obtained also show the need to separate the procedure qualification from the personnel qualification, in order to identify exactly where the problems are, if something should go wrong.

18 RECOMMENDATIONS

From the results and conclusions of the work performed in the NESC 1 project by the Inspection Task Group the following recommendations are made with the purpose of ensuring, as far as is possible, firstly, that the capability of the entire inspection system, including equipment, inspection procedures and personnel, is adequate for the intended purpose, and secondly, that high reliability is achieved when the inspection is performed on-site,

1. For accurate sizing of the through-wall extent of a defect it is recommended that a sizing technique based on the use of the tip-diffracted wave from the defect is employed. However, since inspection teams using this technique did not perform equally well in the NESC 1 study, it is recommended that the inspection system, and personnel, should be qualified on appropriate test specimens and defects.

2. It is recommended that precautions should be taken to reduce the incidence of human error as far as possible. This aim will be assisted by well-written unambiguous procedures both for data acquisition and data analysis, good quality control, training (including on-the-job training) of the inspection personnel. In addition it is recommended that the influence of in-service inspection conditions on the performance of the inspectors should be considered. Some of the factors that should be included in assessment are:
   - inspector motivation and tiredness
   - long working hours
   - shift work
   - pressure of management
   - radioactive conditions
   - tedium

3. It is recommended that when selecting techniques for practical ISI applications, the condition of the cladding should be taken into account when specifying the parameters of the ultrasonic transducers. With optimum probe parameters it should be possible to reduce significantly the influence of cladding on inspection reliability. It is also recommended that the effectiveness of inspection procedures for a specific inspection involving cladding should be verified by inspection qualification methodologies using test specimens with relevant cladding.

4. It is recommended that the fabrication methods used to insert defects in test specimens should be verified to avoid, as far as possible, the inclusion of unintended reflectors in the vicinity of the intended defect.

5. It is recommended that the entire inspection system, including the equipment, inspection procedure and personnel, should verified by inspection qualification

methodologies prior to an on-site inspection to demonstrate that it is capable of meeting the specified inspection objectives. However, in cases where equipment and procedure are accepted by appropriate safety authorities, it may only be necessary for the inspectors to pass suitable personnel qualification examinations.

6. In view of the observation that many of the teams used similar detection and sizing techniques yet obtained different results it is recommended that, following completion of the NESC 1 project, a further analysis of the NESC 1 data be made to investigate the influence of factors such as the quality of: the inspectors; the scanner and equipment; and the data processing equipment and software, on performance. In addition, such studies would analyse the procedures used by the teams that performed particularly well in order to obtain a better understanding of the techniques that could be used to achieve good results. Such studies would require the co-operation of the teams involved, but would be carried out without breaching the confidentiality observed in the round robin trials.

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