INFORMATION FOR THE PROCUREMENT AND CONDUCT OF NDT

Part 4: Ultrasonic Sizing Errors and Their Implication for Defect Assessment

April 2008

Executive Summary

Once defects have been detected in a component, ultrasonic inspection is frequently used to provide information about them to permit an assessment of whether the component is fit for continued service. Data on the size and position of the defects is used in an assessment of structural integrity for this purpose.

The methods used for ultrasonic size and position measurement and the data to be recorded following the inspection must be specified in the ultrasonic procedure. Responsibility for the adequacy of the procedure is with a Level 3 ultrasonic practitioner. The Level 3 practitioner is also responsible for assessing the errors involved and this document provides information on methods of error assessment. Responsibility for use of the ultrasonic data and its associated errors in structural integrity assessment is with a Structural Integrity Engineer. In particular, the decision on the maximum defect size to be used in the calculations i.e. how many standard deviations should be added to the reported values, must be made by the Structural Integrity Engineer. This should be done in a way which ensures that the level of confidence in the ultrasonic sizes used in the calculations is commensurate with the confidence level in the other data used in the process.

Both ultrasonic error assessment and structural integrity analysis can be carried out in a number of ways. Simple methods can be used which provide conservative results. More sophisticated methods of assessment can be used to reduce the conservatisms of the simplified approaches. There is also the possibility of using advanced ultrasonic sizing methods with lower intrinsic errors. If simple methods show that the component is safe to operate in spite of the inherent conservatisms in the methods of calculation, nothing further may be necessary. If, however, the simple methods do not provide a case for continued operation, the more sophisticated measures for error assessment and structural integrity assessment may be able to make the case but usually at the cost of increased time and complexity. What is appropriate in a particular situation must be judged taking into account the significance of the component and the consequences of its failure. This document provides information on how to make such judgements. Three case studies are given to illustrate the use and benefits of increasingly sophisticated methods of integrity and error assessment.

1. Introduction

The Health and Safety Executive (HSE) have been promoting improvements in the reliability of all methods of NDT through the PANI projects [Refs. 1 & 2] and associated best practice documents [Refs. 3, 4 & 5]. Whilst the PANI projects have been primarily concerned with ultrasonic defect detection, sizing data has also been collected and analysed. In PANI 1, the through wall sizing results obtained from the 25 mm thick double V butt weld test piece varied between 2 mm and 10 mm for an 8 mm crack at the weld root and between 2 mm and 10 mm for a 3 mm LOSWF defect. PANI 2 data shows a similar spread of results as illustrated in Figure 1.1.

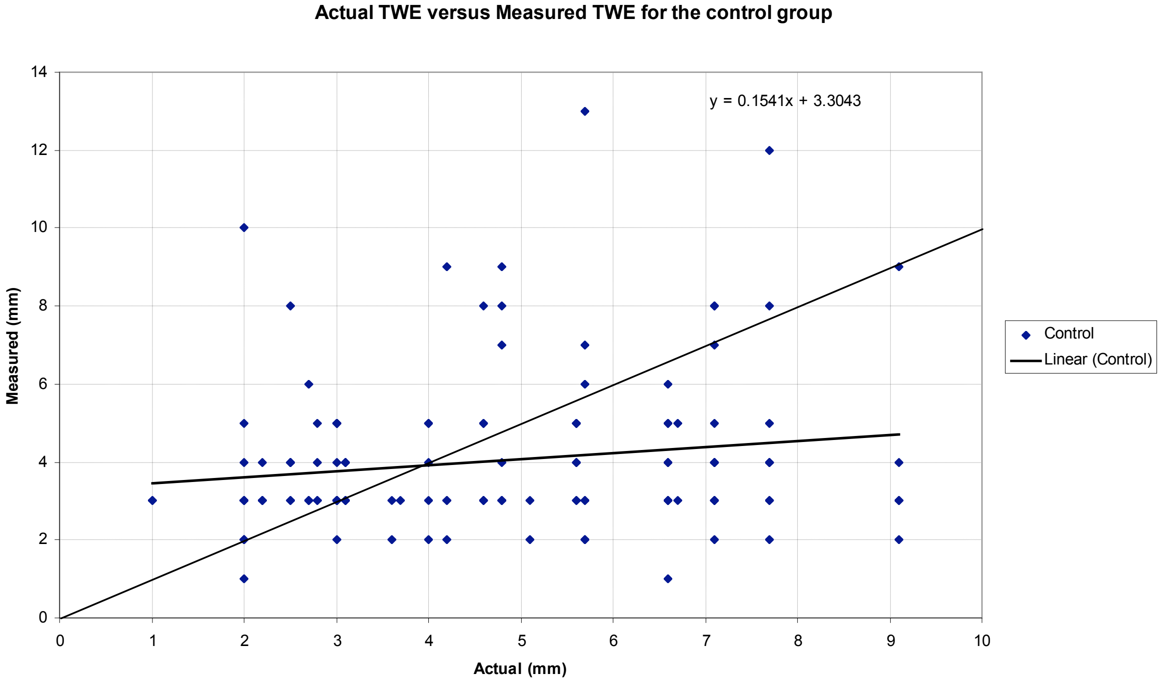


Figure 1.1 Example of the Scatter in Through Wall Sizing Results Obtained in PANI 2

Note: The through wall extent (TWE) of the defect is defined as the perpendicular height of the defect relative to the scanning surface.

The illustration, by the PANI projects and other sources, of the potential errors in ultrasonic sizing, as outlined above, raised HSE's concerns regarding such errors and how they are considered in defect assessment (Engineering Critical Assessment – ECA).

Following the successful production of the HSE documents describing best practice for the procurement and application of manual ultrasonics [Ref. 3], magnetic particle and dye penetrant inspection [Ref. 4] and radiography [Ref.5] and in the light of the above concerns, the HSE have judged it appropriate to issue the present document with a view to promoting the adoption of good practice whenever ultrasonic defect sizing data is used as an input to defect assessment.

This document is oriented towards the inspection of welds because these are a very common location for defects and hence the subject for defect assessment. However, the principles it contains are equally applicable to all component types. The document does not address the errors associated with ultrasonic wall thickness measurements.

The information applies both to inspections and defect assessments carried out by departments of the company owning or manufacturing the plant and to those carried out by external NDT and defect assessment organisations under contract. In the latter cases, it is intended to assist in the procurement process by highlighting the issues that need consideration. In addition, the information draws attention to the need to seek appropriate advice when undertaking any detailed review of the ultrasonic errors or the defect assessment activities.

The information contained in this document is recommended by the HSE for the conduct of defect assessment in industry. The document provides information on how to address the errors inherent in ultrasonic sizing and on how these impact on the defect assessment process. It is intended to raise awareness of the issues and to give information on how an appropriate ultrasonic inspection and defect assessment process can be applied. This document is not intended to replace the relevant technical standards or to supersede them in any way.

The document is primarily concerned with ultrasonic inspection as this is the main NDT method for establishing the through wall size of defects for input to the defect assessment process. Other NDT methods, such as MPI and dye penetrant, may be used to provide additional information on the length of a surface-breaking defect but these are not covered here.

The document has been drawn up by a committee comprising both NDT and structural integrity experts assembled by the HSE for this purpose. Their names and affiliations are given in Appendix 1, from which it will be apparent that they represent a wide range of those parts of British industry using defect assessment based on ultrasonic sizing. In addition, they have considerable expertise in and responsibility for the application of NDT to industrial plant and the assessment of the plant using the results of NDT. The recommendations contained in this document are based on two main sources in addition to the PANI data. The first is a literature search and subsequent review of relevant published papers, international standards and articles regarding ultrasonic sizing errors and defect assessment. The second basis for the recommendations is the collective experience and expertise of the committee mentioned earlier. The members representing the NDT community were also members of the PANI Management Committee [Refs. 1 & 2] and the committees responsible for the previous best practice documents [Refs 3, 4 & 5].

Section 2 describes the data and personnel competencies which are necessary pre-requisites for the sizing and defect assessment process once a defect has been detected. It also describes the responsibilities which the different personnel must assume. Section 3 identifies recommended measures to be applied in determining ultrasonic sizing errors and accounting for them in defect assessments. It is recognised that the extent to which it is reasonable to expend extra effort on the inspection or defect assessment, and incur additional costs as a result, depends on the role of these activities in assuring plant safety, the economics of the activities and the consequences of the activities failing to achieve their objectives. Accordingly, this section refers to the risk classification for components given in the best practice document for manual ultrasonic testing [Ref. 3].

Section 4 gives information on different ways of estimating the sizing errors in an inspection and describes other factors which need consideration. Section 5 provides case studies to illustrate the implementation of the measures given in Section 3.

Background information on uncertainty in measurements and why consideration of this aspect is of increasing importance is given in Appendix 2. The detectability of defects, the sources of error in manual ultrasonic measurements and the uncertainties in defect assessment calculations are discussed. Appendix 3 describes current practice regarding the relationship between defect assessment and NDT and how ultrasonic error estimation and defect assessments are performed. Relevant defect assessment documents and standards are described along with future trends. Appendix 4 defines the terminology so as to avoid confusion in terms which have developed different usages in the NDT and structural integrity disciplines.

2. Pre-Requisites for Ultrasonic Sizing and Defect Assessment

This document provides information on the steps to take once a defect has been detected by a manual ultrasonic inspection.

2.1 Data

Once a defect has been detected, the ultrasonic inspection needs to establish information on the defect for input to the defect assessment. The ultrasonic inspection procedure should specify what information the operator must report. The errors involved in the sizing process should be determined as discussed in Sections 3 and 4 of this document. This may be specified in the procedure or separately.

The information required for the defect assessment which should be specified in the inspection procedure and provided in the inspection report is as follows:

Sizing Techniques. The specific sizing techniques which are used to generate the measurements of any defects should be recorded in the inspection report. This information should include details of the particular ultrasonic probe or probes used to generate the measurement and the length of the beam path from the sizing probe(s) to the defect.

Defect Position. The defect position in the component in three orthogonal axes should be reported. For a weld inspection these three dimensions will normally be along the weld, across the weld and through wall.

Defect Characterisation. The character of the defect should be reported where possible i.e. planar, non-planar.

Defect Length. The measured length of the defect should be reported.

Defect Through Wall Size. The measured dimension of the defect in the through wall direction should be reported. It is important to state exactly what dimension was measured:

> through wall i.e. dimension perpendicular to the surfaces of the component or
> defect height i.e. distance along the face of the defect which may be tilted to the through wall direction as in the case of defects associated with the fusion face of a weld.

Estimate of Errors. The ultrasonic sizing measurements need to be accompanied by an estimate of the uncertainties in the measurements. Estimated values should be provided for both systematic and random errors. The systematic error should be given as a single value. The random error should be given as the standard deviation of the error. The method used to estimate the errors shall also be stated. Different ways in which this can be done are discussed in Section 4.

2.2 Personnel Competencies

The **Level II Ultrasonic Operator** who conducts the inspection should be competent in the application of the required ultrasonic sizing techniques. He / she should be familiar with the application of the ultrasonic procedure including the reporting requirements.

If the procedure requires it, the Level II operator should be familiar with the particular method of estimating the errors in the sizing measurements.

The **Level III Ultrasonic Operator** should be competent in the estimation / calculation and reporting of errors in ultrasonic sizing. He / she should be required to supervise the work and approve both the inspection procedure and the inspection report.

The **Structural Integrity Engineer** should be competent in the application of defect assessments according to BS 7910 [Ref. 6]. He / she should be aware of the methods for estimating ultrasonic sizing errors and the significance of the reported results.

It is incumbent on the plant owner to ensure that competent personnel are used for the various tasks.

2.3 Responsibilities

The **Level II Ultrasonic Operator** is responsible for performing the ultrasonic sizing measurements and reporting the results according to the inspection procedure.

The **Level III Ultrasonic Operator** is responsible for approving the ultrasonic inspection procedure which will specify how the sizing measurements are to be performed. The procedure should specify how the results will be reported and the Level III operator is responsible for checking and approving the inspection report. The Level III operator carries overall responsibility for the estimation of the sizing errors. However, the calculation of the errors can be delegated to the Level II operator if the Level III operator is satisfied that the Level II operator is competent for the task and that the task is appropriately specified in the inspection procedure.

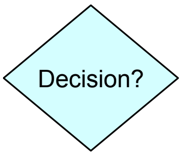
The **Structural Integrity Engineer** has responsibility for undertaking the defect assessment using the information obtained by the ultrasonic inspection. He or she should know the level of confidence that can be placed in the material property values and stress values used in the assessment. These determine the level of confidence necessary when generating the maximum defect size to be used in the defect assessment i.e. the number of standard deviations to be added to the reported size. The Structural Integrity Engineer must therefore assume the responsibility for choosing the maximum size.

3. Recommended Ultrasonic Sizing and Defect Assessment Process

The objective of defect sizing and any subsequent assessment is to permit a demonstration of the fitness for purpose of a component with an appropriate amount of effort. In practice this may mean that the level of assessment is increased step wise with conservatisms in the various sizing and assessment inputs being reduced as is considered appropriate. The process for assessing the ultrasonic sizing errors and the subsequent defect assessment divides into three stages. These are described in the text and illustrated in Figure 3.1, Figure 3.2 and Figure 3.3. The figures should be read in conjunction with the appropriate paragraphs.

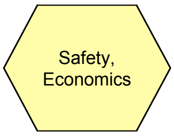
The key to the symbols in the flow charts is given below:

Start or end to the particular flow chart. Green indicates a start or continuation. Red indicates the completion of the process.



Blue diamond indicates a decision is required.

Blue rectangle specifies an activity.

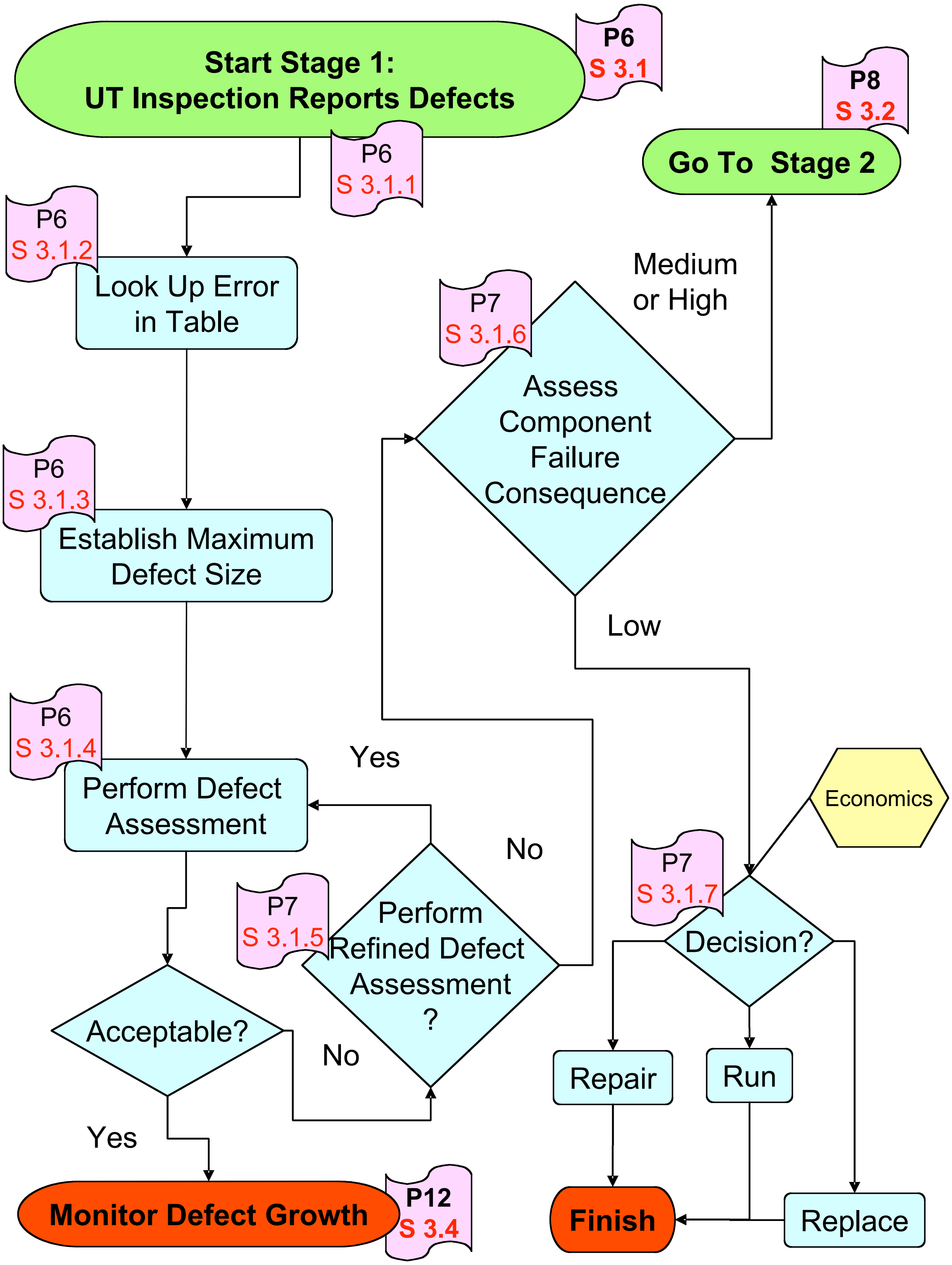


Yellow polygon states factors to be considered in a decision.

Pink “flag” references the page number in black and the section number in red of the text relevant to the item in the flow chart.

Figure 3.1

Stage 1 Process for Establishing Level of Detail of Sizing Error and Defect Assessment Based on Component Failure Consequence



3.1 Stage 1 Process

3.1.1 Ultrasonics Inspection Reports Defects

The starting premise of this recommended practice is as follows:

- An appropriate manual ultrasonic inspection technique has been applied to a component.
- The technique is adequate for the detection of defects of concern.
- The application of the technique has been in accordance with the information given in the HSE's Best Practice document for manual ultrasonic testing [Ref. 3].
- The inspection report shows defects detected and gives the sizes of these defects as measured using conventional manual ultrasonic sizing methods – e.g. maximum amplitude for through wall sizing and 6dB drop for length sizing

Note: Defect assessment can also be performed to establish critical defect sizes and consequently acceptable inspection target defect sizes before an inspection is applied.

3.1.2 Look Up Error in Table

The simplest approach to assessing errors is to use a look up table. Since the generic values in the table represent conservative errors there is no need to embark on a detailed analysis until these values have been shown to be too large to tolerate. Section 4.1 gives values of generic errors that can be used. The values for the random errors are expressed as estimated standard deviations of sizing measurements with reference to the distance along the beam path from the sizing probe to the defect.

The process of selecting and reporting the appropriate values from the table should be supervised by the Level III ultrasonic operator responsible for the inspection.

3.1.3 Establish Maximum Defect Size

The systematic error values in the look up table are used to establish the best estimate of the defect size. The random error standard deviations are used to establish the error bands on the ultrasonic size measurement and hence allow calculation of the maximum defect size.

The Structural Integrity Engineer responsible for performing the defect assessment should decide on what level of confidence is required in the defect size and add the appropriate number of standard deviations to the reported size. The level of confidence in the defect size needs to be commensurate with the confidence in the other data used in the defect assessment.

See Section 4.4.3 on reporting errors.

3.1.4 Perform Defect Assessment

An initial defect assessment is performed using the maximum defect size determined in 3.1.3 above. This initial assessment is likely to be performed as a basic Level 1 assessment as defined in BS EN 7910 [Ref. 6]. However, the decision on what Level assessment to apply is the responsibility of the Structural Integrity Engineer. See Appendix 3 for more details.

If this is found to be acceptable according to the assessment criteria, then no further work is required and the process ends with monitoring of the defect as described in Section 3.4.

If the maximum defect size is found to be unacceptable then there is the option to revise the defect assessment as described in 3.1.5.

3.1.5 Perform Refined Defect Assessment?

A Level 1 defect assessment will usually have been performed with conservative materials or stress data and simplifying assumptions regarding the shape of the defect. The assessment can be repeated using the more advanced Level 2 assessment process [Ref. 6]. Such a process may require several iterations with various degrees of complexity. If this Level 2 assessment process is sufficient to show the defect to be acceptable then no further work is required and the process ends with monitoring of the defect as described in Section 3.4.

If a re-assessment is not possible, is not preferred or the re-assessment still shows the defect to be unacceptable, then subsequent actions will depend on the consequence of component failure, as described in 3.1.6.

3.1.6 Assess Component Failure Consequence

The best practice document on manual ultrasonic inspection [Ref. 3] describes how the risk of a component failure, and the role of inspection in reducing the risk, is established. The risk of failure is the product of failure probability and the consequence of a failure. The next step for the defect assessment process described here depends on the consequences of the component failing. The consequences are classed as low, medium or high.

If a component classed as low failure consequence fails, it will have little safety or economic consequence. Having found a defect, which on the initial defect assessment is sentenced as unacceptable, a decision on what to do with the component needs to be taken as described in Section 3.1.7. The effort required to refine the ultrasonic errors is unlikely to provide added benefit for this class of components.

Defects in medium and high failure consequence components require a more considered approach and this is described in Stage 2, Section 3.2.

3.1.7 Decision on Low Consequence Component

A defect has been found in a low failure consequence component. The defect has been sized. The uncertainty in the sizing has been estimated using the look up tables and the defect assessed. The assessment has shown that the defect is unacceptable and is likely to lead to the failure of the component. The plant operator has three options:

1. Recheck consequence of failure and if confirmed as low and acceptable, continue to operate the component. Consider operating the component in a way which reduces the probability of failure e.g. change the operating pressure or temperature.
2. Replace the component.
3. Repair the component.

Repairing or replacing the component removes the defect and the sizing / assessment process is finished. Leaving the component in service also completes the process. The plant operator has the option to monitor the defect during continued operation. Monitoring has the potential to allow maintenance to be planned.

3.2 Stage 2 Process

The stage 2 process gives the recommended actions for assessing defects in components categorised as medium or high failure consequence.

3.2.1 Decide Initial Actions.

Using the results of the initial defect assessment which sentenced the defect as unacceptable, the plant owner needs to decide between a number of possible options. If the initial assessment indicated that the magnitude of the sizing errors was sufficient to make the defect unacceptable then these can be refined either by performing a more accurate calculation of the errors (Section 3.2.2) or by performing repeat inspections and size measurements (Section 3.2.3).

If these two actions are not considered appropriate or unlikely to significantly alter the acceptability of the defect, then the plant owner can opt to repair the component, replace the component or apply a more accurate sizing technique (Section 3.2.7). Repairing or replacing the component removes the defect and the sizing / assessment process is finished.

Another possibility may be to operate the component in a way which reduces the possibility of failure e.g. by changing the temperature or pressure of operation. In this situation, it would be necessary to go back to Step 3.1.4 to determine whether the defect is tolerable under the new operating conditions.

3.2.2 Calculation of Errors

The initial determination of errors based on the look up tables will produce conservative estimates. More precise values calculated for the particular inspection conditions are likely to reduce these conservatisms and hence the maximum defect size. One method of calculating errors is illustrated in Section 4.2. The decision to calculate sizing errors for the particular inspection lies with the Structural Integrity Engineer whilst overall responsibility for such calculations is with the Level III ultrasonic inspector even if the actual calculations are carried out by a Level II inspector.

3.2.3 Repeat Inspections

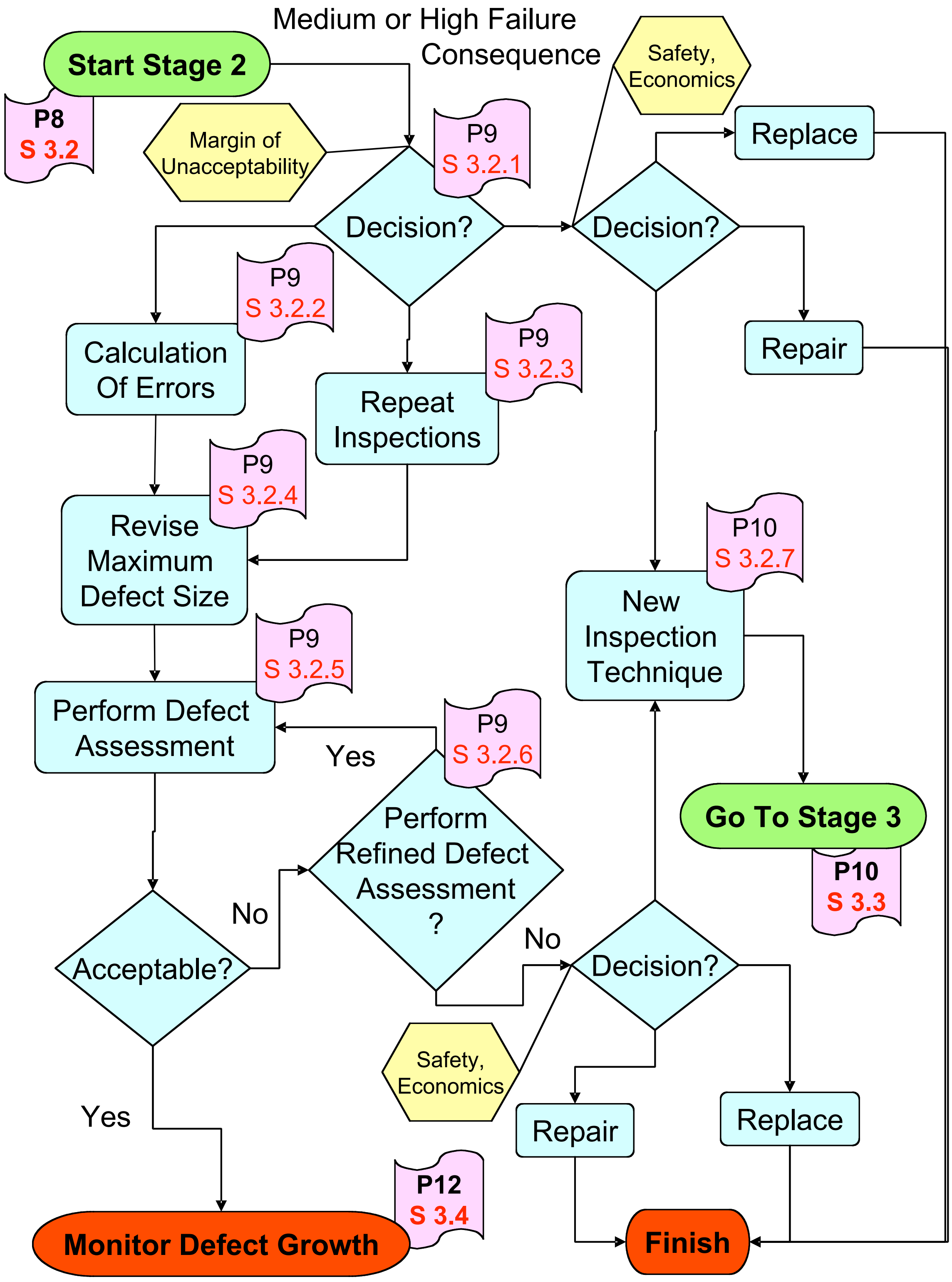
An alternative method of reducing the error in a measurement is to independently repeat the measurement. The random error in the combined measurement is reduced by the square root of the number of measurements, as described in Appendix 2 Section A2.1.

3.2.4 Revise Maximum Defect Size

Both error calculation and repeat inspection are likely to provide reduced error bands for size measurements performed by the particular inspection under review. This in turn will allow a revised, less conservative value of maximum defect size to be used in structural integrity assessment.

Figure 3.2

Stage 2 Process for Establishing Level of Detail of Sizing Error and Defect Assessment for Components with High or Medium Failure Consequence



3.2.5 Perform Defect Assessment

A defect assessment will be performed using the revised maximum defect size. The level of rigour of the assessment will be commensurate with the failure consequence classification of the component and will depend on the results of the initial Level 1 assessment performed under 3.1.4.

If this is found to be acceptable according to the assessment criteria, then no further work is required and the process ends with monitoring of the defect as described in Section 3.4.

3.2.6 Perform Refined Defect Assessment?

If the revised maximum defect size is found to be unacceptable then there is the option to revise the defect assessment. If only a Level 1 assessment has been performed previously then the more detailed Level 2 assessment would be the next step. If a Level 2 assessment has already been performed (and with various degrees of complexity) then it may be beneficial at this stage to perform laboratory or site tests or measurements to obtain more accurate data on the material properties or residual stresses in the component for input to the revised defect assessment.

Refining the error calculation and improving material and stress data reduces the conservatism in assessing defect acceptability. The optimum choice of what refinements to make depends on the situation and requires a case by case judgement by the Structural Integrity Engineer.

If a re-assessment is not a preferred option or the re-assessment still shows the defect to be unacceptable then, considering the safety and economic implications, the plant owner has the option to repair or replace the component or to apply a more accurate sizing technique as described in section 3.2.7.

Repairing or replacing the component removes the defect and the associated uncertainty and the sizing / assessment process is finished. However, repairs need to be carefully controlled so that they are not a source of new defects which could threaten the integrity of the component

3.2.7 New Inspection Technique

If the errors in standard manual ultrasonic inspections are considered to be too large for the particular application, then alternative inspection techniques may be applied. Examples include: TOFD; automated pulse echo; use of focussed probes or arrays. The application of an improved sizing technique is described in Stage 3, Section 3.3.

3.3 Stage 3 Process

Having decided to implement an improved sizing technique, an assessment of the errors inherent in the application of such a technique should be made as described below.

3.3.1 Qualify Sizing Technique

Having arrived at Stage 3 of the process for high or medium consequence components, it is recommended that qualification for defect sizing be carried out to establish the sizing capability of the selected technique for the particular circumstances of the inspection.

Qualification is defined as the systematic assessment, by all those methods that are needed to provide reliable confirmation, of an NDT system to ensure it is capable of achieving the required performance under real inspection conditions. An NDT system is the combination of inspection procedure, equipment and personnel. In this case the required performance would be the sizing performance.

Qualification can be a complex and costly process, particularly when numbers of test pieces are needed. The extent of the qualification, therefore, needs to be appropriate to the particular inspection requirements. It may be that a theoretical analysis of the sizing technique is sufficient or that practical trials alone may provide the required evidence. However, defect sizing is often demanding, very skill dependent and prone to being influenced by quite subtle factors. Consequently, for situations where high levels of inspection (sizing) effectiveness must be demonstrated or where there is little previous experience of an inspection, e.g. when novel inspection methods are planned, blind trials on realistic defects in adequate simulations of the real component are necessary.

3.3.2 Perform Inspection & Report Maximum Defect Size

The errors established in the qualification exercise can be used to modify the measured defect size and the maximum possible defect size reported for input into the defect assessment. Also, having qualified the sizing technique, it is important to ensure that the technique is applied correctly on-site.

3.3.3 Perform Defect Assessment

If the process has been followed from stage 1, then an initial defect assessment will have been performed either at Level 1 or Level 2. The defect assessment performed now in stage 3 will be a more comprehensive Level 2 assessment using data which is consistent with the effort input into to establishing small sizing errors. This may include iterations and sensitivity analyses being performed. If Level 2 assessment is not considered appropriate, then a Level 3 assessment can be performed. In fact, a Level 3 assessment may be the most appropriate assessment in situations where brittle fracture can be ruled out. However, such an assessment can be quite involved and is likely to only be used in special circumstances.

If this shows the defect to be acceptable according to the assessment criteria, then no further work is required and the process ends with monitoring of the defect as described in Section 3.4.

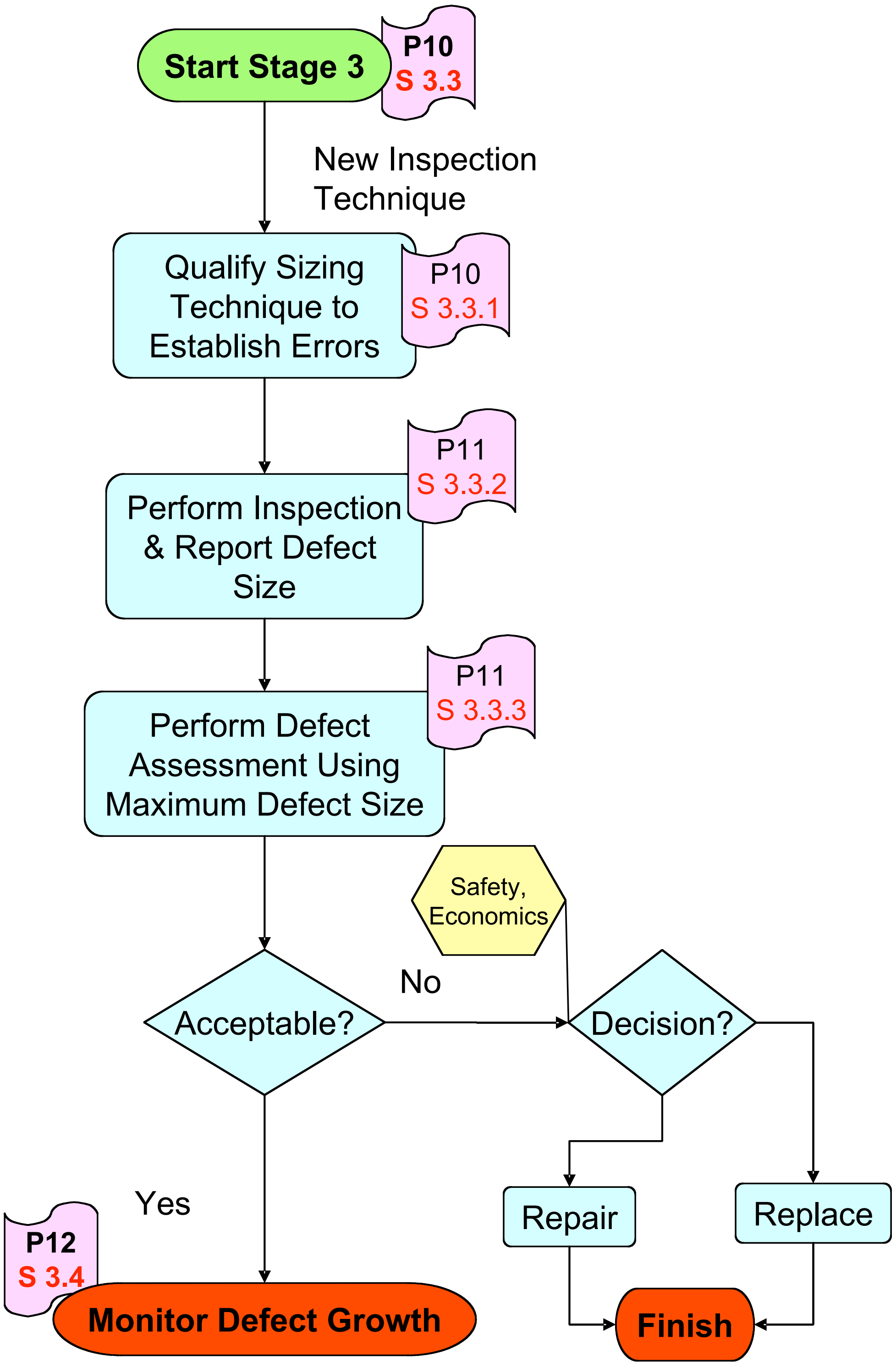
If the defect is shown to be unacceptable, then, other than going back to Section 3.2.7 and identifying a more precise sizing technique, the plant owner has two principal options - to repair or replace the component. Repairing or replacing the component removes the defect and the associated uncertainty and the sizing / assessment process is finished. However, repairs need to be carefully controlled so that they are not a source of new defects which could threaten the integrity of the component. The possibility of operating the component in a different way as discussed in Section 3.2.1 could also be considered.

3.4 Monitor Defect Growth

The monitoring of defects for evidence of growth in-service has additional requirements beyond those required for the sizing of a defect and is beyond the scope of this document. The issues involved in comparing sizing measurements for signs of growth are briefly described in Appendix 2 Section A2.3.

Figure 3.3

Stage 3 Process for Establishing Level of Detail of Sizing Error and Defect Assessment Based on Component Risk



4. Estimating Errors

Three increasingly complex methods of estimating errors have been mentioned in Sections 3.1.2, 3.2.2 & 3.3.1. These methods are:

1. Look Up Error in Table
2. Calculate Error
3. Qualify Sizing Technique

The application of each method is described below and illustrated in the case studies given in Section 5.

4.1 Method 1: Look Up Error in Table

The generic error values given in Figure 4.1, Table 4.1 and Section 4.1.2 are based on the following assumptions:

- The ultrasonic sizing of a defect is subject to separate systematic and random errors.
- The systematic errors are a function of the technique employed and are fixed values.
- The random errors vary from measurement to measurement and are expressed as estimated standard deviations of this variation.
- The standard deviation of the random errors increases with increasing distance along the beam from the sizing probe to the defect and so increases with component thickness.
- The occurrence of single, large errors, otherwise referred to as “blunders”, which occur when an operator makes a significant mistake such as reading or transcribing 25 instead of 250, have not been addressed. The chances of these occurring need to be minimised by appropriate management of the NDT process.

4.1.1 Through Wall Sizing

Maximum amplitude sizing is the preferred technique for through wall sizing.

The systematic error for maximum amplitude sizing is 1 mm undersizing when locating the position of one edge of the defect. For an embedded defect where the size requires the location of two edges the systematic error becomes 2 mm [Ref.7].

The standard deviation of the random error to be used with the through wall size measured by the maximum amplitude technique is given in Figure 4.1 and Table 4.1. These figures have been selected as conservative values based on data from the PANI 2 project [Ref. 2], the capability statements in ESI 98-10 [Ref. 8] and errors calculated using the CEGB Code of Practice [Ref. 7].

Distance Along Beam From Sizing Probe to Defect	Random Error Standard Deviation
20 mm	± 3 mm
100 mm	± 4 mm
200 mm	± 5.5 mm
300 mm	± 7 mm

Table 4.1 Estimate of Standard Deviation of Random Errors for Maximum Amplitude Through Wall Sizing

Error Look Up Table (Length Sizing – 6dB Drop: Through Wall Sizing – Maximum Amplitude)

Through Wall Sizing

Systematic Error

Use 1 mm undersizing for location of 1 defect edge (e.g. surface breaking defects)
Use 2 mm undersizing for location of 2 defect edges (e.g. embedded defects)

Systematic Error is: _____ mm Undersizing

Length Sizing

If measured length is adjusted to account for any curvature of scanning surface then:

Systematic Error is: 0 mm

Standard Deviation of Random Error is: ± 10 mm

Through Wall Sizing - Standard Deviation of **Random Error**

Establish Distance Along Beam from Sizing Probe to Defect & Look up Value of Error for that Distance

Standard Deviation of Random Error is: _____ mm

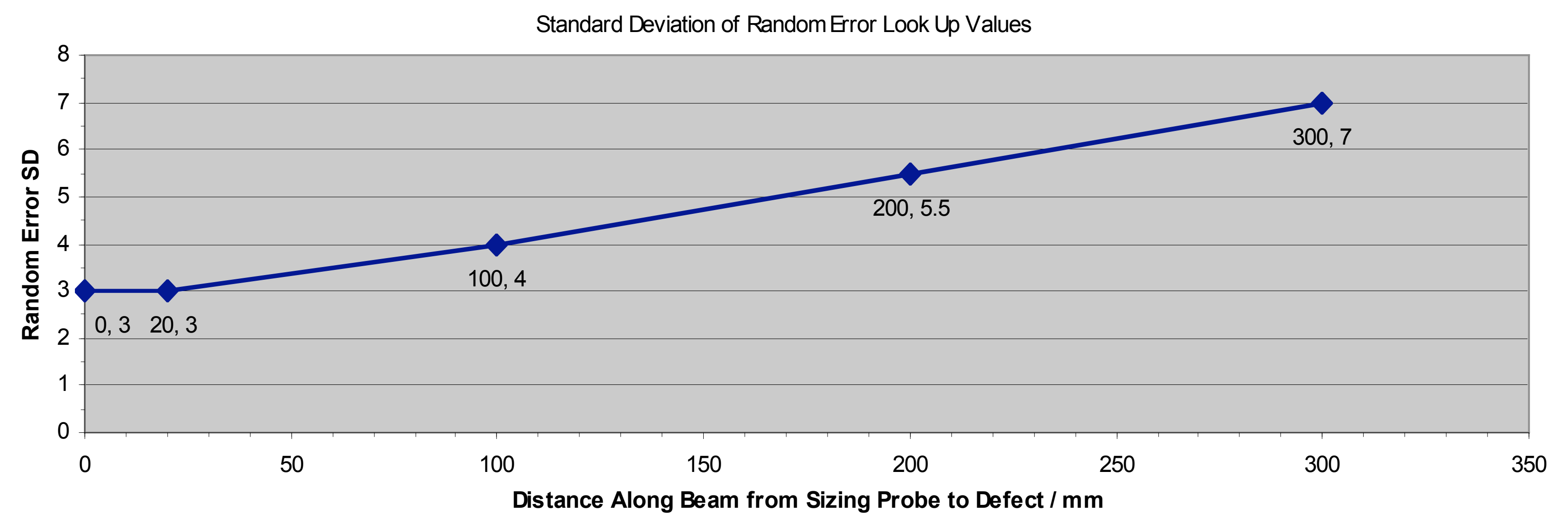


Figure 4.1 Error Look Up Table For Through Wall Sizing (Maximum Amplitude Technique) and Length Sizing (6 dB Drop Technique)

When the distance along the beam from the sizing probe to the defect is below 20 mm, use ± 3 mm as the random error standard deviation. For values in between those given above, use linear interpolation i.e. for 150 mm distance use ± 4.75 mm.

4.1.2 Length Sizing

The preferred technique for length sizing is the 6 dB drop technique. The systematic error for this technique is zero.

Whilst the errors are likely to have some variation with range to the defect and hence component thickness it is appropriate to have a single estimate of **± 10 mm** for the standard deviation of the length sizing random error.

4.2 Method 2: Calculation of Error

An alternative and more accurate estimate of the sizing errors incurred in a specific inspection can be obtained by considering each individual source of error in the sizing measurement and combining the values to obtain an overall error. Figure 4.2 shows the steps in the error calculation process. One example of an application this process is described in a CEGB Code of Practice [Ref7].

The CEGB Guidance Document

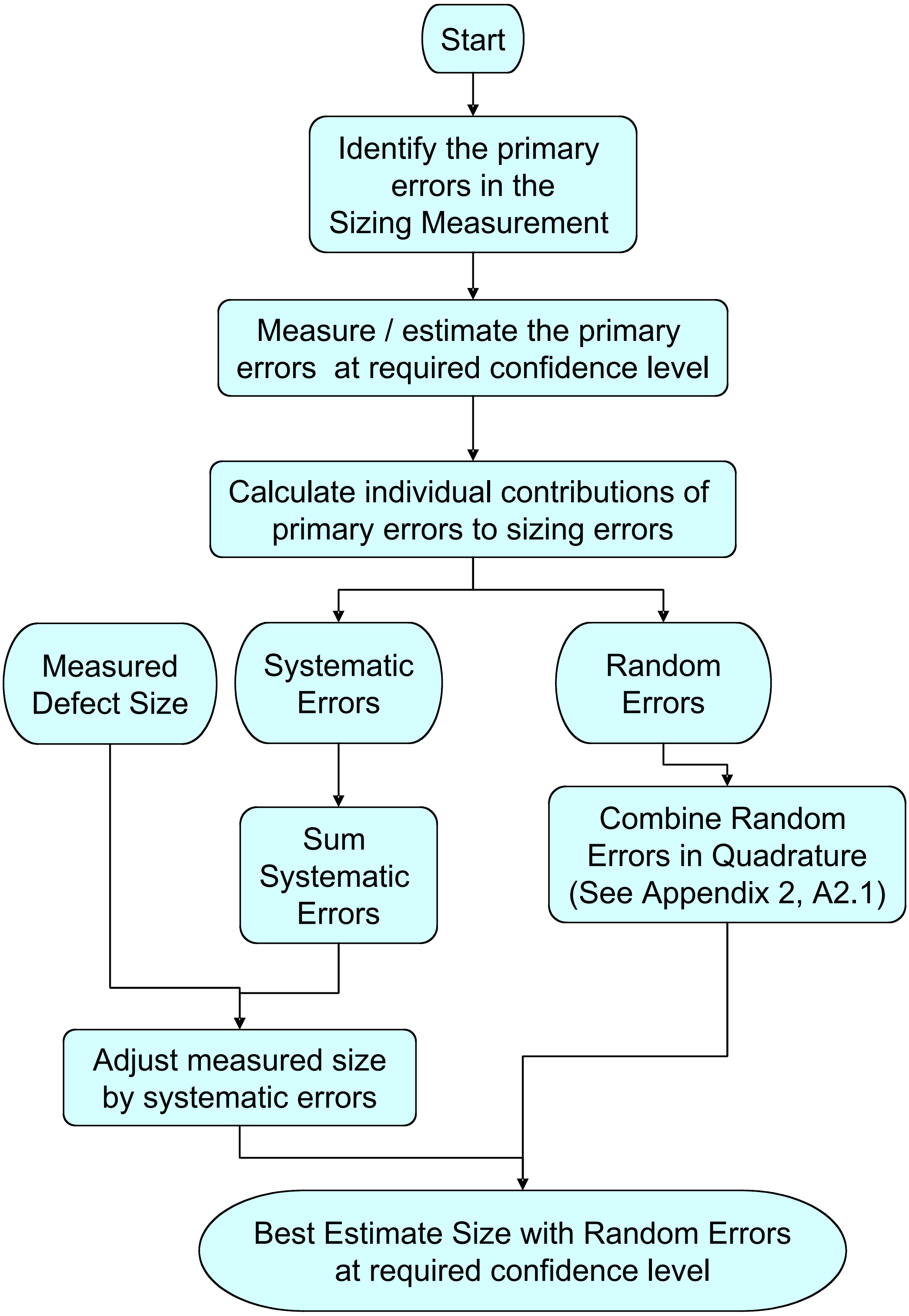
Note: The CEGB Guidance document illustrates the application of a general methodology for assessing errors in measurements to the particular circumstances of manual ultrasonic sizing. It identifies the primary measurement errors and their subsequent contribution to the reported size. It also provides estimates of the primary errors at 80% confidence limits. The document was first produced in 1987. PDF copies of the CEGB document can be requested by e-mail from ROGER.LYON@RWEnpower.com on the understanding that this is an old document and potential users should satisfy themselves that the estimates of primary errors are consistent with their company practices for manual ultrasonic sizing.

British Energy has produced an updated version of the document with revised estimates for some of the primary errors. Enquiries regarding the availability of this updated document should be made in writing direct to British Energy at

Dr Bob Chapman,
British Energy plc,
Barnett Way,
Barnwood,
Gloucester,
GL4 3RS

Figure 4.2

Process for Calculating Errors in Sizing Measurement



It is important to note that:

1. The CEGB Code of Practice provides values or formula for calculating the magnitude of the contribution of the particular primary error to the sizing error. The estimates for the primary error are given at an 80% confidence level. Hence, the calculated magnitude of the contribution of the particular primary error to the sizing error will also be at the 80% confidence level.

   If a higher level of confidence is required or if different primary errors are identified in a particular assessment, then a new estimate of the primary error will be required. This can be produced either as a Type A or Type B standard uncertainty (See Appendix 2).

2. The Code of Practice provides a methodology for calculating errors in manual ultrasonic sizing using a single probe. The use of a scanning jig is also covered, as is the combination of separate measurements from the same probe. Errors in sizing may be reduced by the use of automated inspection systems and the combination of measurements from different probes. These are not covered in the Code of Practice.

4.3 Method 3: Qualify Sizing Technique

Qualification involves a combination of:

- Practical trials of the inspection conducted on simplified or representative test pieces resembling the component to be inspected.
- Technical justification which involves assembling all the evidence available on the effectiveness of the inspection including previous experience of its application, laboratory studies, mathematical modelling, physical reasoning etc.

The relationship between the practical trials and the technical justification depends on the particular inspection. However, they are almost always complementary parts of the overall qualification process. The technical justification is likely to contain a similar error calculation to that described in section 4.2. The practical trials may be used to test the sizing technique and provide experimental evidence of its capability. They may also be used to test the ability of the NDT operator in applying the technique within the required error band or to test both the technique and the operator. This qualification process may be overseen by an independent qualification body to provide additional confidence in the inspection.

Usually the errors are calculated in a theoretical assessment and they are then supported by practical trials and used as the limits to establish operator pass / fail criteria in a blind trial.

It is important that high failure consequence items of plant receive the appropriate level of assessment to ensure their integrity. The ideal overall scenario for dealing with high risk items is as follows:

- Establish that the features, dimensions, materials and weld identification are given on the design drawings and confirm that they have accurately been followed through to the actual structure or component.

- Based on engineering judgement, stress analysis/materials properties, past experience, risk based inspection etc. or a combination of these, specify the locations to inspect and the defects requiring detection.

- Perform initial defect assessment evaluations to establish defect sizes to target in NDT.

- Select and specify the NDT techniques to employ for the various locations to meet the designated requirements.

- Qualify the NDT techniques and inspectors using an appropriate combination of technical justification and replicate samples.

- Use the qualification to consider and establish probability of detection and sizing accuracy.

- Perform inspection with appropriate control – audit, witnessing, repeat inspections.

- Perform detailed defect assessment evaluations with consideration of the significance of sizing errors.

4.4 Other Considerations When Performing Defect Assessment

4.4.1 Position Measurement.

The sizing of defect indications requires the positioning of the edges of the defect. Therefore, the errors in positioning the centre or one edge of the defect will follow a similar procedure to that used to establish the errors in measuring the defect size.

4.4.2 Ligament Measurement

Similarly, the measurement of a remaining ligament is dependent on the location of the edge of a defect. Care needs to be taken to ensure that the sense of the errors is correct. A systematic undersizing in the location of a defect edge will give a systematic oversizing of the remaining ligament and vice versa.

4.4.3 Reporting Errors

The requirements for reporting the results of an inspection need to be agreed between the NDT and defect assessment personnel. The CEGB Code of Practice [Ref. 7] gives two alternatives:

Best Estimate

The best estimate size of a defect is the measured defect size adjusted by the systematic errors and reported with the bounds of the random errors. For example if a defect is measured at 10 mm with a systematic under sizing of 2 mm and a standard deviation of random sizing errors of ± 2.5 mm then the best estimate size is:

12 mm ± 2.5 mm

One standard deviation either side of a mean covers 68% of the data for a normal distribution. So there is 68% confidence that the actual defect size will lie in this range.

The errors in the CEGB code of practice are given for a confidence level of 80% and so the reported best estimate result with 80% confidence is:

12 mm ± (2.5 * 1.28) = 12 mm ± 3.2 mm.

Upper or Lower Bound

Fracture mechanics is often interested in the worst case situation. For a defect this will be the largest defect size or upper bound. However, whilst there is 80% confidence that the defect size will lie in the range 12 mm ± 3.2 mm, there is 90% confidence that the defect will be less than or equal to 15.2 mm.

Hence the defect given in the above example would then be reported as:

Upper bound 15.2 mm at 90% one sided confidence (standard deviation of random error ±2.5 mm allowed for).

Alternatively, if the defect is near the surface of a component, fracture mechanics may require knowledge of the smallest remaining ligament. For a ligament measured as a best estimate of 8 mm ± 3 mm at 80% confidence then:

Lower bound 5 mm at 90% one sided confidence (standard deviation of random error ±2.3 mm allowed for).

It is recommended that the results are presented on a scale engineering drawing showing the best estimate of defect position, form, size and orientation.

The reporting of sizing errors needs to be consistent with the geometry of the component. The error shouldn't take the defect outside of the component wall.

However the results of the inspection are reported, the sizes and the errors should be clear and unambiguous and the confidence limits should be given.

5. Case Studies

The following case studies give examples of the use of each of the different approaches of ultrasonic sizing error estimation and subsequent defect assessment.

5.1 Method 1: Defect Assessment Based on Look up Table Errors

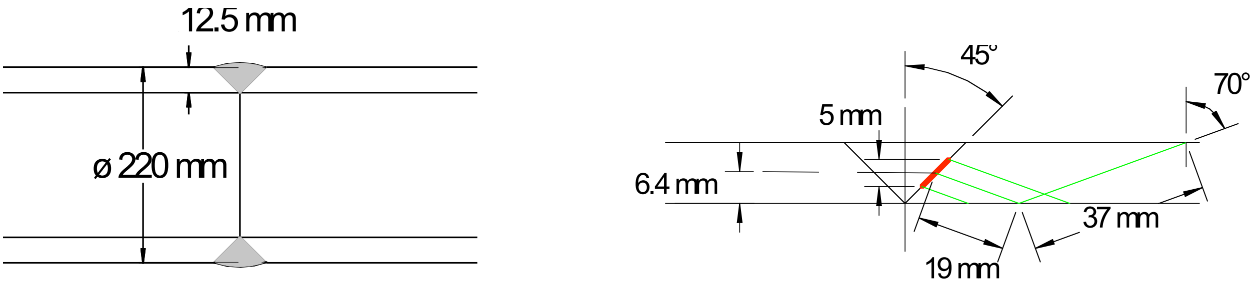


Figure 5.1 Geometry of Pipe Inspection & Defect Detected

An ultrasonic inspection has been performed on the pipe geometry shown in Figure 5.1. The pipe operates at 1570 psi and 300ºC. The pipe and weld material has yield strength (σ_Y) of 250MPa and ultimate strength of 430 MPa, and the weld has been subjected to post weld heat treatment (PWHT). The fracture toughness of the material (K_{mat}) is 80MPa√m.

As shown in the figure, a defect was detected on the fusion face with the 45° probe giving a large amplitude response. The maximum amplitude sizing technique was applied using the full skip by a 70° beam. The reported through-wall size, perpendicular to the scanning surface was 5 mm with a length of 50mm. The position of the defect within the pipe was reported as on the pipe wall centre line. (Start Stage 1).

The sizing errors are estimated using the values given in Section 4.1.1 and Figure 4.1 (Stage 1 Look Up Error in Table).

The systematic error for the maximum amplitude technique is 2 mm undersizing so the best estimate of through wall size for the defect is 5 + 2 = 7 mm.

The distance along the beam between the sizing probe and the defect is (37 + 19) = 56 mm so the standard deviation of the random error read from the graph in Figure 4.1 or obtained by interpolating between the values given in Table 4.1 is 3.5 mm.

So the defect would be reported as a best estimate of 7 mm with a standard deviation of random error of ± 3.5 mm. In order to achieve a similar level of confidence as the other defect assessment input data, the Structural Integrity Engineer uses a confidence level of 80% which equates to 1.28 standard deviations.

Hence the maximum through wall defect size is:

7 + (3.5 * 1.28) mm = 11.5 mm
(Stage 1 Establish Maximum Defect Size)

As this is the estimate of the maximum defect size, there is 90% confidence that the actual size will be less than this.

The standard deviation of the random error in the defect length, from Section 4.22, is ±10 mm. Adjusting this to 80% confidence to be consistent with other defect assessment input data gives a maximum length of the defect as:

50 + (10 *1.28) = 63 mm

The position of the defect within the weld is assumed to be reported correctly, with no errors applicable, for the purpose of this case study.

The defect assessment is then performed using the methods described in BS7910:1999 [Ref. 6] for a "Level 1 Simplified Assessment". (Stage 1 Perform Defect Assessment).This process is described as follows:

a) For a cylinder under pressure, the relevant principal stress for this circumferential embedded defect is identified as the axial direction.

b) The hoop and axial stress levels are calculated based on the pressure loading.

c) The most suitable solutions for this embedded defect in BS7910:1999 are for an embedded defect in a plate.

d) The fracture ratio (K_r) is determined based on the stress intensity factor (K_I) solution provided for an embedded defect in a plate. Residual stress is added to the axial stress for the calculation of K_I.

e) K_r is given by the equation: $K_r = K_I/K_{mat}$ and is equal to 0.155

f) The load ratio (S_r) is determined based on the reference stress (σ_{ref}) solution provided. This reference stress is based on the axial stress and does not include residual stress. As this solution is based on the Tresca yield criterion, which considers only two principal stress values, the resulting (axial) reference stress is compared with the hoop stress. The highest of these two stress values is used as the reference stress to calculate the load ratio, S_r. In this case, the highest stress is that calculated based on the axial reference stress.

g) S_r is given by the equation: $S_r = \sigma_{ref}/ \sigma_f$ and is equal to 0.86. (Note: σ_f is the flow stress, equal to $1.2\sigma_Y$ in this case).

h) When these K_r and S_r parameters are plotted as an assessment point on the Level 1 FAD (Failure Assessment Diagram), the specified flaw size leads to failure based on S_r as illustrated in Figure 5.2. The result of an assessment based on the measured defect through wall and length sizes, without any adjustment for errors, is also shown on Figure 5.2 for comparison.

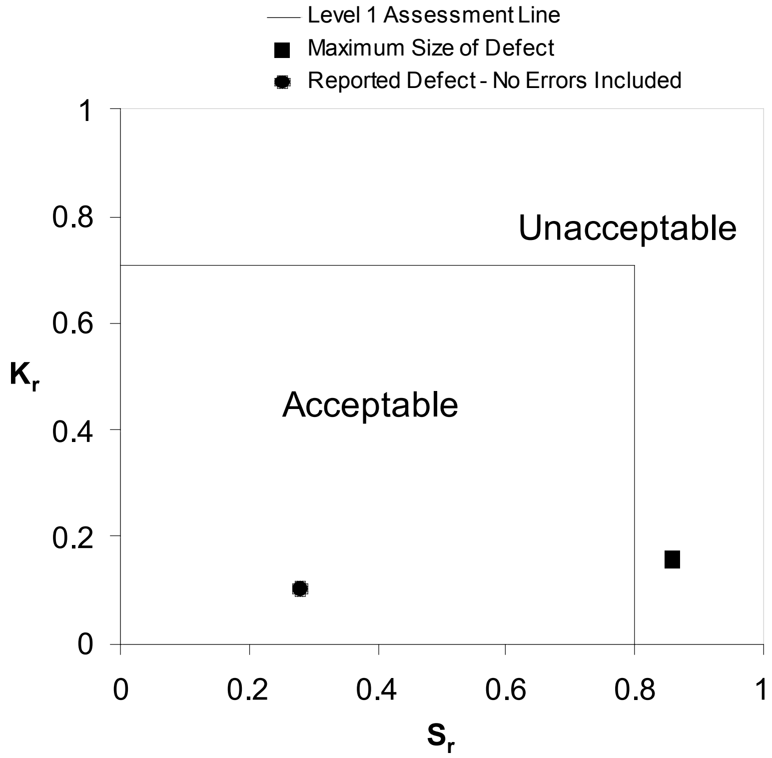


Figure 5.2 Level 1 Failure Assessment Diagram for Case Study 5.1

As can be seen the maximum possible defect size using the errors from the look up table cannot be justified for safe operation (Stage 1 Acceptable?). As shown in the flow sheet given in Figure 3.1 there are a number of options now open to the plant owner:

1. The defect assessment can repeated using the Level 2 assessment process.
2. The section of pipe could be repaired.
3. The section of pipe could be replaced.
4. The failure of the pipe can be assessed from a risk viewpoint. If the failure of the pipe has low consequences (low consequence) then the owner may opt to continue operation with the defect in situ. If failure of the pipe would have medium consequences then an option is to refine the estimate of the errors in the ultrasonic sizing measurement. (Stage 2, 1st Decision). As the initial assessment placed the defect just outside the Level 1 assessment line, then calculating revised ultrasonic sizing errors appears to be a potentially beneficial option. The next section describes the methodology of this error refinement in detail.

5.2 Method 2: Defect Assessment Based on Calculation of Error

(Stage 2 Calculation of Error)
The process of manual ultrasonic sizing needs to be broken down into its individual steps in order to identify each source of error as described in Appendix 2, Section A2.3. The CEGB Code of Practice [Ref. 7] provides one method of calculating these individual sources of error and combining them to derive an overall estimate of sizing

error for a particular beam angle / defect configuration. This approach has been applied to the defect reported in Section 5.1 above, and is explained below.

For information regarding the CEGB Code of Practice see the text box in Section 4.2.

5.2.1 Calculation of Through Wall Sizing Error

The following calculation of the error in sizing the defect, is based on the CEGB Code of Practice Table 1 for defect through wall sizing by 2-edged techniques: defect dimension perpendicular to the scanning surface. Note that probe positioning errors have no effect on through wall sizing or positioning when the through wall direction is perpendicular to the scanning surface.

The individual errors are identified and calculated. The errors are numbered as in the Code of Practice. S denotes a systematic error and E denotes a random error.

S1 & E1. Inherent Errors in Sizing Technique

The inherent errors in the sizing technique are both systematic and random. For the Maximum Amplitude technique these are estimated at 80% confidence to be:
Systematic Error S1= 2 mm (undersizing)
Random Error E1= ± 2.5 mm

E2. Range Calibration Error in the Flaw Detector

The error in calibrating the flaw detector is estimated at 2%. The contribution this makes to the sizing error is given by a formula which includes the ranges to the top and bottom of the defect, R1 and R2, and the beam angle, θ.

In this case R1 = 47 mm R2 = 61 mm θ = 70°

The error E2 is calculated as ±0.1 mm.

E3. Beam angle calibration error

The beam angle calibration primary error is estimated at 1° and the contribution to the sizing error is calculated at ±0.24 mm. Again the ranges and the beam angle are the parameters in the error equation.

E8. Range Reading Error

The estimate of the primary error is based on reading the range of the signal from an analogue flaw detector screen. This is estimated to be ±0.5 of the small graticules. The formulae includes the calibration reflector range and the beam angle and gives the value for E8 as ±0.48 mm.

E9 Error Due to Timebase Non-linearity.

For an analogue flaw detector this is estimated as 1% of the full screen width. The error calculated from the calibration range and the beam angle, E9, is ±0.48 mm.

E10 Draughting Error

The contributing errors are estimated to be 1 mm in plotting the range for each edge and 0.5° in plotting the beam angle. The formulae, based on R1, R2 and θ, give a combined error for E10 of ±0.8 mm.

E11 Beam Angle Error Due to Error of Form on Scanning Surface

Any error in form on the surface of the component will tip the beam and effectively alter the beam angle. This is likely to be worse on a ground weld cap than on parent plate, hence the estimates of the error are 1° for the weld cap and 0.4° for parent plate. For the inspection under review the probe is on the parent plate and so the formula gives a value of ±0.51 mm for E11.

E12 Error Due to Coupling Variations Caused by Surface Finish

This error source provides a random error contribution for the maximum amplitude technique. Again the difference between scanning on a ground weld and the parent plate is taken into account. Calculating the relevant formulae in Table 1 of the CEGB Code of Practice gives the following value for scanning on the parent plate:
E12 = ±0.57 mm for maximum amplitude

Combination of Errors

Maximum Amplitude Technique

This technique has one systematic error S1 of 2 mm undersizing.

The relevant random errors are summed according to the following formula:

$$E = \sqrt{(E1^2 + E2^2 + E3^2 + E8^2 + E9^2 + E10^2 + E11^2 + E12^2)}$$

$$E = \sqrt{(6.25 + 0.01 + 0.0576 + 0.288 + 0.288 + 0.64 + 0.26 + 0.285)}$$

$$E = \pm 2.8 \text{ mm}$$

So having been sized by the maximum amplitude technique at 5 mm through wall, based on these calculated errors, the defect would be reported as a best estimate of 7 mm ± 2.8 mm. The Code of Practice provides error estimates at 80% confidence and so there is no need to adjust this best estimate for the defect assessment process used in these case studies.

So the maximum defect size that would be used in the defect assessment would be:

9.8 mm
(Stage 2 Revise Maximum Defect Size)

5.2.2 Calculation Of Length Sizing Error

The following calculation of the error in the length sizing of the defect is based on the CEGB Code of Practice Table VII Defect Length Sizing.

The technique used for length sizing is the 6 dB drop technique.

S1 & E1. Inherent Errors in Sizing Technique

The 6 dB drop technique does not have an inherent systematic error. The inherent random error is estimated at 80% confidence to be:
E1= ± 3 mm

E7. Error in Reading the Probe Position

The primary error for reading probe position is estimated as 1.5 mm. This converts to a length size error of 1.8 mm according to the formula.

E10 Draughting Error

Draughting error is estimated as 1 mm for each edge so that the combined error is 1.4 mm.

E13 Error due to Skewing of the Probe

When scanning the probe to locate the end of the defect the manual operator may skew the probe. The primary error is estimated as 3° and this will lead to a length error of 2.7 mm.

S14 Systematic Error Due to the Curvature of the Scanning Surface

When scanning on the external surface of the pipe, the length as measured on the surface will be greater than that of the actual defect at some depth below the surface due to the curvature. If this is not accounted for in the procedure then it will cause a systematic oversizing of the defects. For the situation in this case study pipe inspection this systematic error would be 7.6 mm oversizing.

Combination of Errors

Systematic Errors – The only systematic error would be, S14, the error due to the curvature of the scanning surface, if this had not been addressed in the inspection procedure and taken into account when plotting out the defect.

Assuming that the adjustment had not been made in the procedure, the best estimate of defect length would be:

$$50 \text{ mm} - 7.6 = 42.4 \text{ mm}$$

Random Errors – The random errors are combined in quadrature so that the total random error is given by:

$$E = \sqrt{(E1^2 + E7^2 + E10^2 + E13^2)}$$

$$E = \sqrt{(9 + 3.24 + 1.96 + 7.29)}$$

$$E = \pm 4.6 \text{ mm}$$

As described earlier, this result is calculated at 80% confidence.
So having been reported at 50 mm length, as measured by the 6dB drop technique, and with the curvature of the pipe not having been taken into account, the maximum length to be input to the defect assessment is:

42.4 (best estimate) + 4.6 = 47 mm

The defect sizes for input into the defect assessment are summarised in Table 5.1. The maximum defect sizes incorporate the most onerous systematic and random error values.

Measurement			**Maximum Size**
	Systematic	**Random**	
Through Wall	+2 mm	± 2.8 mm	9.8 mm
Length	-7.6 mm	± 4.6 mm	47 mm

Table 5.1 Maximum Defect Sizes for Input into Defect Assessment for Case Study 2.

5.2.3 Defect Assessment Based on Calculated Errors

(Stage 2 Perform Defect Assessment)

The defect assessment is then performed following the same steps as were taken in Section 5.1. The assessment results based on the calculated sizing errors are given in Table 5.2 along with those obtained in Section 5.1 for the look up table errors and those that would have been obtained if there had been no estimate of errors and the defect size was taken as measured.

NDT Method / Error Method	**Basis of Defect Size Used in Assessment**	S_r	K_r
Maximum amplitude	Calculated Errors	0.368	0.143
	Look Up Table Errors	0.86	0.155
	Measured Defect Size Without Errors	0.28	0.102

Table 5.2 Summary of Failure Assessment Results

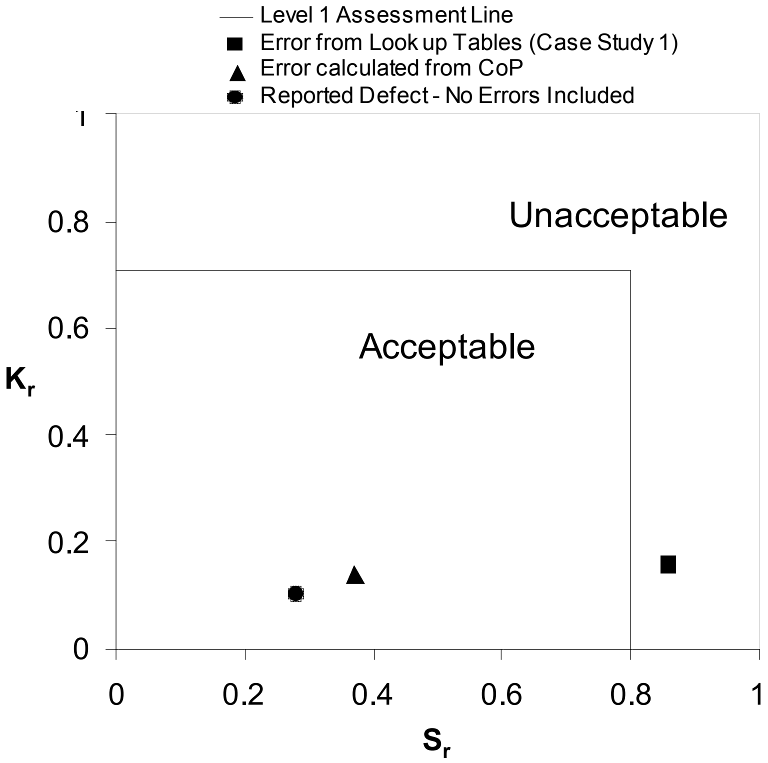


Figure 5.3 Failure Assessment Diagram for Case Study 2

Figure 5.3 shows how this result plots on the Level 1 Fracture Assessment Diagram relative to the points based on the look up errors and on no error assessment at all. (Stage 2 Acceptable Decision) Clearly, the assessment point based upon the specific error calculations is beneath the level 1 assessment line, and the defect is therefore now deemed acceptable. The defect can therefore be left in the pipe and monitored (Stage 2 Monitor Defect Growth).

This case study illustrates the benefit that can come from calculating the error margins for specific NDT methods, in terms of decreasing the pessimisms in the assessment process.

5.3 Specific NDT Technique and Full Assessment

An operator had three refrigerated, low pressure, storage tanks that had been in service in excess of 30 years. The potential damage mechanism was stress corrosion cracking (SCC). In order to assess integrity, the periodic inspection was to enter the vessel every 12 years, and use extensive magnetic particle inspection (MPI) to identify and quantify any SCC. Previous inspections from inside the tanks had found no SCC. All inspections had found minor defects that were categorised as original manufacturing defects. The repair carried out on these defects was to blend the cracks out by grinding. To carry out an inspection from inside the tank required considerable work to ensure that the tank was suitable for entry, and the process of re-commissioning the tank had to be carefully controlled, as this could induce the SCC.

The Competent Person wished to use non-invasive inspection, NII, (i.e. inspection applied to the external surface of the tank) to remove the requirement for decontamination and refilling. The exercise was to provide confirmation that there was no SCC present. While considerable past inspection data was available, the following data was not available:

i) The fracture toughness of the parent, weld and HAZ materials.
ii) The maximum tolerable defect size.
iii) The area of maximum stress
iv) The NDT technique that could detect the required size of defect originating on the internal surface of the vessel when inspecting from the outside.

The first of these tanks was inspected by a conventional internal inspection, and, while the tank was decommissioned, four, circular, test samples were taken. These samples were used through a mechanical test programme to obtain the fracture toughness for the parent plate, weld and HAZ. Finite element calculations were carried out to identify the areas of maximum stress, and then a fracture assessment was carried out to BS 7910. These calculations indicated that a defect height of approximately 10mm in the through wall thickness was the maximum tolerable.

This size of defect could be easily detected by the use of conventional pulse echo ultrasonics from the outside of the wall, but the detection and sizing had to be qualified to ensure that the use of NII and a different NDT technique gave an equivalent inspection to the prior internal inspections. To demonstrate this, a test plate was manufactured with defects of varying size and orientations. The heights of the defects were based on reporting size for the NDT inspection, which was at least a factor of two less than the maximum allowable. An NDT specialist qualified to PCN Level 3, produced a procedure using focused ultrasonic probes. During trials this procedure was qualified for detection and sizing.

For the actual vessel inspection, the test piece was used to qualify the sizing capabilities of the NDT service providers. All operators were PCN level 2, but it was found that only 50% of the operators could size the defect within the tolerance required.

By using fracture mechanics to establish the tolerable defect size, and the use of a specific NDT procedure, the Competent Person established that the use of a NII strategy was valid.

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Appendix 1 - Members of the Document Drafting Committee

John Whittle	(Chairman),	Independent Consultant
Adam Bannister		Corus Group
Barrie Shepherd		Mitsui Babcock
Bob Andrews		Advantica
Harry Bainbridge		HSE
Henryk Pisarski		TWI
Stuart Hewerdine		Aker Kvaerner
Neil Henry		ABB
Rick Gregory		ExxonMobil
Roger Lyon		RWE NPower
John Sharples		Serco Assurance
Bernard McGrath	(Secretary)	Serco Assurance

Appendix 2 - Uncertainty in Measurements

Generally, the result of any measurement is only an estimate or an approximation of the actual value of the quantity being measured (the measurand). The difference between the measurement and the measurand is the error of the measurement. As the measurand is unknown it follows that the actual error is unknown. Uncertainty is a parameter which characterises the spread of measurement values which could reasonably expected from a particular value of the measurand. A measurement result can therefore only be assessed to see if is suitable for use in a particular application if it is accompanied by a quantitative statement of its uncertainty.

Estimating uncertainty in measurements has become increasingly important due to the recent issue of: BS EN ISO/IEC 17025:2000 – **“**General requirements for the competence of testing and calibration laboratories”. This standard requires the laboratories to assess and report uncertainties and so accreditation authorities require evidence that this is being done.

A2.1 Introduction to Uncertainty in Measurements.

Uncertainty can be expressed in a number of ways but a common way is to use what is termed “standard uncertainty”, i.e. the standard deviation of the possible values of the measurement. If a measurand is not measured directly but derived from a series of other measurements, as is the case in NDT, then the uncertainty is estimated from combining the individual uncertainties of the separate measurements.

The International Organization for Standardization (ISO) have produced a “*Guide to the Expression of Uncertainty in Measurement*.”[1], which provides assistance in the methods of evaluating and expressing uncertainty. A few key definitions are provided below:

There are two main ways of estimating standard uncertainty.

Standard Uncertainty - Type A is the standard deviation derived from statistical analysis of a number of actual observations.

Standard Uncertainty – Type B is an estimated value of standard deviation, usually based on scientific judgment using all of the relevant information available. Such information may include previous measurement data, and experience with, or general knowledge of, the behaviour and property of relevant materials and instruments.

The uncertainties which arise in individual measurements can be due to two classes of error – systematic errors and random errors.

Random Errors

These are errors which change from one measurement to the next and which can shift the measurement in either direction so that the mean error will be zero if sufficient measurements are taken. Examples of sources of such errors are the

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[1] ISO“*Guide to the Expression of Uncertainty in Measurement*.”, International Organisation for Standardisation (ISO), 1995 ISBN 92-67-10188-9

rounding up or down of readings and insufficient sensitivity in the measuring instrument so that small changes can not be discerned.

Systematic Errors

These are errors which tend to shift all measurements in a systematic way so their mean value is displaced. This may be due to such things as incorrect calibration of equipment, improper use of equipment or not accounting for some effect. In defect sizing the actual technique used to size a defect can have a systematic error which tends to undersize a defect.

Combination of Errors

If a value (X) is derived from the combination (sum or difference) of two independent measured values (A and B) then the error in the derived value is equal to the square root of the sum of the squares of the errors in the two measured values, i.e.

$\Delta Z = \sqrt{(\Delta A^2 + \Delta B^2)}$

This is because the errors in A and B will not necessarily have the same sign and so whilst in one instance they may give an increased overall error, in another case they may cancel each other out.

A2.2 Detectability of Defects

A common misconception with NDT is that it is always 100% reliable. Before sizing uncertainty can be considered, a defect has to be detected. So in addition to deciding whether the defects found by NDT are acceptable, it is also necessary to consider what may be the largest flaw which may have been missed by the NDT technique.

One common method of describing the ability of an NDT technique to detect defects of a particular size, either length or through wall height, is through Probability of Detection (POD) values. These values are generally displayed as a curve of POD against increasing defect size. Figure 1 shows a typical POD graph. The probability of missing a defect is then given by 1- (POD value).

Other forms of detection reliability data exist, one of which is obtained by plotting the POD against the probability of a false indication (PFI). Such a plot is described as a Relative Operating Curve (ROC) and there will be different curves for different sizes of defect.

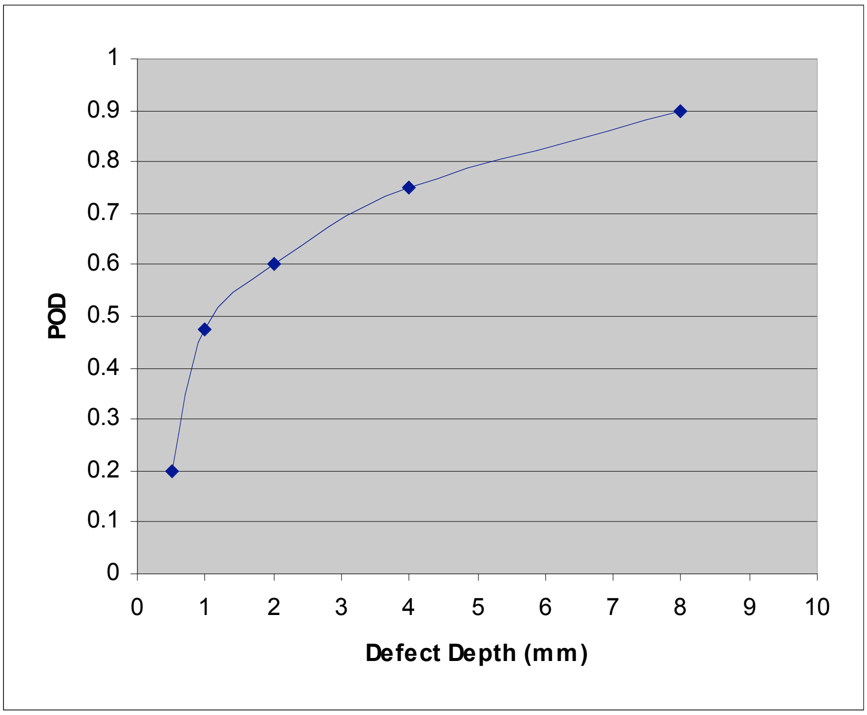

Figure 1 Typical Form of POD Curve

The discussion of POD is outside the scope of this document and information can be found elsewhere[2]. However, it is worth noting the following:

- Care needs to be taken when using POD data in order to ensure that the POD values have been obtained from exercises or models which are relevant to the particular inspection where they are being applied.

- POD data is often based on experimental values. Sufficient measurements need to have been taken to allow statistically valid conclusions to be drawn. The smaller the number of measurements on defects of a particular size, the lower the confidence which can be placed in the results.

- The actual POD of an inspection is the sum of the intrinsic capability of the system**,** the effect of application parameters such as surface finish, access etc, and the effect of human factors[3]. A technique may have a high intrinsic capability for detecting the defects of concern but if environmental and human factors are not managed correctly the detection capability will be impaired.

- The overall POD can be increased by the application of independent, repeat inspections. If a manual ultrasonic inspection has a POD of 50% then the possibility of missing a defect is 1-0.5 = 0.5. The possibility of missing a defect in two separate inspections is 0.5*0.5 = 0.25 so the overall POD of the two inspections is (1-0.25) = 0.75.

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[2] Visser, W., “POD / POS Curves for Non-destructive Examination”, HSE Offshore Technology Report 2000/018, ISBN 0 7176 2297 5

[3] Müller (Nockemann), C., Golis, M., and Taylor, T., “Basic Ideas of the American-European Workshops 1997 in Berlin and 1999 in Boulder”, 15th NDT World Conference, Rome 2000

A2.3 Sources of Error in Manual Ultrasonic Measurements

Once a defect has been found, then the assessment requires that its dimensions, length and through wall, are measured. The manual ultrasonic sizing process will inevitably incur errors even when the defect signals are clear and unambiguous and the operator applies the process without mistakes. These errors are the random and systematic errors associated with the measurement tasks as described in section 2.1. Larger sporadic errors may be made by the operator, such as plotting the beam angle as 55° instead of 45°. These blunders are harder to predict and are not covered in this document other than to warn of their existence.

An example of a method for assessing the random and systematic errors in manual ultrasonic testing was produced by the CEGB in 1987[4] [5]. Fourteen sources of primary error are identified in the document:

1. Inherent errors in the sizing technique
2. Range calibration error in the flaw detector
3. Beam angle calibration error
4. Probe 20dB beamwidth measurement error
5. Probe index point location error
6. Scanning frame positioning error
7. Probe position reading error
8. Error in reading echo range from flaw detector screen
9. Flaw detector non-linearity
10. Plotting errors
11. Effect of surface error of form on beam angle
12. Coupling variations due to surface finish affecting the beam angle
13. Inadvertent skewing of the probe
14. Systematic error due to curvature of scanning surface

Errors such as 1 and 12 can have both random and systematic components. Most of the others are just random errors. Some, such as 4 and 6, apply to a particular technique, others, such 3 and 5 will apply in all cases.

The CEGB Code of Practice provides formulae for calculating the magnitude of the contribution of these individual errors to the overall sizing error. The formulae are based on the signal being clearly visible on the flaw detector screen. Larger errors would be incurred if the defect signal was mixed in with geometric echoes such as weld root responses. The Code of Practice does not cover the calculation of defect sizes from measurements from different probes.

Key factors in the calculation of the magnitude of the individual errors are the beam angle and range to the indication. Some of the sources of error have changed since this code of practice was issued. For example, digital flaw detectors can now give range readings of echoes rather than the operator having to interpolate between graticules on the screen.

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[4] Chapman, R. K. "Code of Practice. The Errors Assessment of Defect Measurement Errors in the Ultrasonic NDT of Welds," CEGB Guidance Document , OED/STN/87/20137/R Issue 1 July 1987

[5] Worrall, G. M., Chapman, R. K. and Seed, H., "A Study of the Sources of Sizing Error Incurred in Manual Ultrasonic NDT", Journal of BINDT, INSIGHT Vol. 37 No. 10 October 1995

The use of other alternative ultrasonic techniques may remove some sources of error observed in manual inspections but may also introduce new ones.

Defect Growth.

When using manual ultrasonics to detect or monitor defect growth, the errors in the individual size measurements need to be established. A statistical test then needs to be applied to establish whether or not the difference in these measurements does indicate growth or whether it is due to errors in the measurement. The CEGB Code of Practice explains this process in detail.

The implication of this process, however, is that a high level of confidence that defect growth has occurred can only be obtained from a change in measured size between two measurements which is greater than the errors in the individual measurements.

When performing this analysis, a compromise needs to be made between missing defect growth when growth has occurred and identifying growth when in fact none has occurred.

A2.4 Uncertainties in Defect Assessment Calculations

In addition to defect size, a defect assessment process requires input of material properties, such as toughness (e.g. Charpy energy, K_{ic}, CTOD) and tensile properties (e.g. yield and ultimate tensile stress), and predicted applied stress levels both operational and residual. It also uses inputs from crack growth laws and failure modes. All of these inputs have associated uncertainties.

Laboratory measurements of material properties are subject to similar measurement uncertainties as ultrasonic sizing. Stress values are often estimated in the absence of practical measured values. As a consequence, conservatisms are often built into both sets of parameters.

Appendix 3. Current Practice

A3.1 Relationship between Defect Assessment and NDT

The relationship between defect assessment and NDT can occur in two ways:

- In many cases, NDT will find a defect which is then subsequently assessed to establish the fitness for purpose of the component.
- Alternatively, a component may be assessed structurally and the critical defect size established. From this value an inspection target defect size can be derived and the inspection is then designed to reliably detect and size defects of the target size and above.

A3.2 Ultrasonic Sizing Considerations

There are three principal conventional manual ultrasonic sizing techniques:

1. 6dB Drop Technique
2. Maximum Amplitude Technique
3. 20 dB Drop technique

6 dB drop technique – this is applicable to the sizing of smooth defects larger than the width of the beam in the direction of the sizing measurement when hit at normal incidence in the plane of the measurement. It relies on the assumption that when the centre line of the beam hits the edge of the defect, only half the beam is incident on the defect and therefore the amplitude of the signal will be half (i.e. 6dB lower) that of the signal observed when all the beam hits the defect (maximum amplitude observed).

The condition for applying 6dB drop sizing is that the echo dynamic in the direction of the sizing measurement exhibits a Pattern 2 response as described in the European Standard[6]. If this technique is applied to defects smaller than the beam then the measurement tends to give the beamwidth rather than the defect size, leading to oversizing.

As the beam moves away from normal incidence the response from the defect becomes distorted from the ideal Pattern 2 response and identifying the 6 dB drop point becomes difficult, leading to errors in the sizing measurement.

Maximum Amplitude technique – this is applicable to the sizing of defects where the beam is incident on the defect at an oblique angle and a Pattern 3 response as described in the European Standard is observed. The probe is moved to maximise the last peak in the signal before it disappears. For smooth planar defects this peak corresponds to the diffracted signal generated by the edge of the defect. For rough defects the edge diffracted signal is often hidden by the echo from the last facet of the defect. Hence there is a systematic error in the technique which leads to an undersizing.

20 dB Drop Technique – this is similar to the maximum amplitude technique but instead of maximising the echoes from the tips / last facets of the defect, the edges of

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[6] BS EN 1713:1998, “Non-destructive Examination of Welds. Ultrasonic Examination. Characterization of Indications in Welds

the beam where the amplitude has fallen to 20 dB below that on the beam centre line is used. As with the maximum amplitude technique there is a systematic error which leads to an undersizing of the defect. The 20 dB drop technique can be used on defects smaller than the beam and can be applied to defects exhibiting either Pattern 2 or Pattern 3a / 3b responses. However, as it uses the 20 dB pulse echo beam profile, which will depend on the directivity of the reflector, it is important that the beam profile is plotted on a range of targets of similar form to the defects requiring sizing.

Sizing of defects using the maximum amplitude and 20 dB drop techniques requires that the echoes from either edge of the defect be resolved. This means that there is a minimum size of defect below which it is not possible to size. The resolution of echoes along the beam depends on the pulse length and this tends to be better than the resolution perpendicular to the beam which depends on the beamwidth. When sizing defects at oblique incidence, the actual resolution is a combination of the two depending on the actual angle of incidence. ESI 98-10[7] gives typical values for the minimum measurable defect size as:

3 mm for defects at depths of 25 to 75 mm
5 mm for defects at depths of 75 to 125 mm

A3.3 Ultrasonic Errors

The current approaches to dealing with errors in ultrasonic sizing vary in complexity as detailed below.

1. Do Nothing.
   Often, there is a willingness to accept results at face value. Thus, when an inspection reports no defects, the component is assumed to be defect free. Likewise when an ultrasonic inspection reports a defect size at 5 mm, it is believed that the defect actually is 5 mm.

2. Generic
   Where it is accepted that an uncertainty exists in ultrasonic sizing measurements, the difficulty in deciding an appropriate value for the uncertainty is simplified by using a generic figure in all instances. In ultrasonics a value of ±3 mm is commonly used. Although the basis for this figure is uncertain, the errors which generally have the largest influence on the overall sizing errors are the random errors inherent in the sizing techniques and estimates of these errors are in the region of ±3 mm.

3. Broad Estimate of Errors
   The next level of detail is to modify the generic error figure to suit broad ranges of inspection parameters. ESI standard 98-10 gives an example of ultrasonic capabilities for defect positioning and sizing. An example of part of the table is given in Table 1. All dimensions are in millimetres.

   The asymmetric error bands in the tolerance column indicate a tendency of probe movement techniques to undersize defects (taking into account the systematic error). The interpretation of these tolerance figures is as follows: an

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[7] "Manual Ultrasonic Testing of Welds in Ferritic Steel Sections: Part 4 – Guidance on Inspection Capability and Joint Design", Issue 1. Electricity Supply Industry, ESI Standard 98-10 Part 4, 1988

actual 10 mm defect in the depth band 25 – 75 mm (tolerance +2, -5) will be sized in the range 5 mm to 12 mm. Alternatively, a defect sized as 10 mm will actually lie in the range 8 mm to 15 mm.

Capability	Ultrasonic Reflector Type	Embedded Defects		
		Depth Below Surface	Minimum Measurable Size	Tolerance
Through Thickness Sizing Accuracy	Volumetric, Planar, Multiple	5 – 25	3	+1, -4
		25 – 75	3	+2, -5
		75 – 125	5	+4, -7

Table 1 Extract From ESI 98-10 Giving Broad Estimates of Sizing Errors

4. Specific Estimate of Errors
   For situations where the safety of a high risk component relies on the results of an ultrasonic inspection, it is often necessary to make a specific estimate of the errors involved in any sizing measurement.

   The CEGB Code of Practice was originally developed to assist in this process and allow calculation of specific sizing errors by summing all the individual sources of error. An alternative practical approach was implemented by British Gas[8] in which a test piece trial was conducted with a number of operators sizing representative defects.

   The use of calculations or trials to established uncertainty is often done within inspection qualification. This provides a framework for specifying the level of confidence and the sizing requirements and for applying the appropriate level of rigour in the uncertainty analysis. It also requires the process to be documented.

5. Specific NDT Following Full Assessment
   In the case of high risk components, it is likely that a full defect assessment will be performed prior to any NDT. This assessment will determine the critical defect sizes for the component and therefore allow calculation of the defect target sizes that the NDT must be capable of detecting. The assessment will also determine the limits for the sizing errors of the NDT. The NDT technique can then be designed to achieve these targets and inspection qualification applied to show that it actually does achieve them in practice.

A3.4 Defect Assessment

A3.4.1 Defect Assessment Process

A summary of the defect assessment process according to BS 7910[9] is as follows:

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[8] Andrews, R. M. and Morgan, L. L. “Using ECA with Real NDT Data “, I. Mech. E. Seminar, June 1999

[9] BS 7910:1999, “Guide on methods for assessing the acceptability of flaws in metallic structures

1. Identify the flaw type (that is whether it is planar or non-planar, a strip or an ellipse)

2. Establish the essential data, relevant to the particular structure. This includes

    - Materials data evaluated to various standards. This should take account of the material strain and thermal history and the environment and cover all loadings.
    - Details of flaw, i.e. position, surface breaking or embedded and orientation
    - Structural and weld geometry, fabrication procedure
    - Stresses and temperatures including transients
    - Tensile properties (yield strength, tensile strength etc.)
    - Fatigue/corrosion fatigue S-N and crack growth data
    - Fracture toughness properties (can be estimated from Charpy V-notch data in certain cases)
    - Creep rupture, creep crack growth & creep fatigue

3. Determine the size of the flaw

4. Assess possible material damage mechanisms and damage rates

5. Determine the limiting size for the final modes of failure

6. Based on damage rate, assess whether the flaw would grow to this final size within the remaining life of the structure or the in-service inspection interval, by sub-critical crack growth

7. Assess the consequences of failure

8. Carry out sensitivity analysis

9. If the flaw would not grow to the limiting size, including appropriate factors of safety, it is acceptable. Ideally the safety factors should take account both of the confidence in the assessment and of the consequences of failure

Several different levels of treatment of flaws are possible, for fracture, according to BS 7910. These are referred to as Level 1, 2 and 3. Level 1 uses a simplified, conservative model. Level 2 removes some of these conservatisms and allows for refinement of the assessment. Level 3 is an advanced procedure which requires a high level of materials data. For fatigue and creep crack growth there are procedures when specific materials data are provided and guidance for when specific information is not available.

A3.4.2 Relevant Standards and Documents

As mentioned above the main document for defect assessment is BS 7910. The relevant sections of the document which refer to NDT are:

> Section 6.3, which is a general section introducing NDT. This has a sub section that requires that: “suitable allowances should be incorporated in the assessment of flaw sizes to cover intrinsic and measurement errors involved and thereby ensure conservative assessment of flaw severity. These allowances and their bases should be quoted in the ECA.”

Note: ECA refers to "Engineering Critical Assessment" which is an alternative terminology for "Defect Assessment".

Annex C – Fracture Assessment Procedures for Pressure Vessels and Pipelines – This warns that ultrasonic sizing is subject to errors and therefore, safety factors should be applied to flaw sizes reported by ultrasonics.

Annex H – Reporting of Fracture, Fatigue or Creep Measurements – This requires allowance to be made for sizing errors and also sensitivity analysis to be undertaken against parameters such as flaw size, material properties, loading conditions.

Annex K – Reliability, Partial Safety Factors, Number of Tests and Reserve Factors – This has various sections which are relevant to NDT.

Other sources of information on defect assessment are given below.

A European project Structural Integrity Assessment Procedure for European Industry (SINTAP), was undertaken with the aim of developing a procedure for subsequent standardisation of fracture mechanics based flaw assessment methods on a European level[10]. Section II.3 of the procedure is on flaw characterisation and there is a supporting document which provides information on the effectiveness of NDT [11].

A subsequent European network has been set up to produce new Engineering Critical Assessment procedures. This is known as FITNET – http://www.eurofitnet.org/

The American Petroleum Institute produces a number of documents relating to inspection and defect assessment. Recommended Practice API 579 Fitness for Service[12] describes standardised fitness-for-service assessment techniques for pressurized equipment used in the petrochemical industry. This recommended practice is intended to supplement the requirements in:

API 510, Pressure Vessel Inspection Code: Maintenance Inspection, Rating, Repair, and Alteration[13].

API 570, Piping Inspection Code: Inspection, Repair, Alteration, and Re-rating of In-service Piping Systems[14]

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[10] SINTAP (1999), "Structural Integrity Procedure for European Industry". Brite-Euram Project Report, European Union Document

[11] "Compilation of NDE Effectiveness Data", SINTAP Task 3.4 Final Report, European Commission JRC, Institute of Advanced Materials, March 1999

[12] Recommended Practice 579 Fitness-For-Service (ANSI/API RP 579-2000 1st Edition / January 2000

[13] Pressure Vessel Inspection Code: Maintenance Inspection, Rating, Repair, and Alteration, API 510 ANSI/API 510-2000

[14] Piping Inspection Code: Inspection, Repair, Alteration, and Re-rating of In-service Piping Systems, API 570 ANSI/API 570-2000

API 653 Tank Inspection, Repair, Alteration, and Reconstruction[15]

A3.5 Future Trends

In Section A3.3 the use of defect assessment techniques to derive target defect sizes for input into the inspection design was described. Recent developments in this area have taken this a step further and used the defect assessment process to define the acceptance criteria for automated ultrasonic testing (AUT) of pipeline welds.

A potential negative effect of the commercial pressure to use improved and cheaper NDT alternatives is the difficulty in comparing results between inspections performed with different techniques. Differences in both detection and sizing capability will need to be assessed and quantified in order to allow comparison to take place and statements regarding defect growth to be made.

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[15] Tank Inspection, Repair, Alteration, and Reconstruction, API 653 3rd Edition/ December 2001

Appendix 4. Terminology

Best Estimate	The measured size or position adjusted to account for the systematic errors in the measurement.
Blunder	Gross, isolated error in an activity due to a human mistake.
Confidence Interval	The measurement interval within which a true parameter value lies with a given probability (see also confidence level).
Confidence Level	The confidence level for an interval determines the probability that the confidence interval produced will contain the true parameter value. . A probability associated with a confidence interval is a two sided confidence level. A probability associated with an upper or lower bound is a one sided confidence level.
Confidence Limits	The end points of a confidence interval at a specified confidence level.
dB Drop	Method of ultrasonic sizing by identifying the positions where a signal drops in amplitude by a specific amount from the maximum, usually 6 dB or 20 dB.
Defect	Unintended discontinuity in a component which may impact on the integrity or quality of the component.
Defect Assessment	The analysis of a defect in a component to establish whether the defect will cause failure of the component. Alternatively, it can be used to establish the size of a defect that would threaten the integrity of the component..
ECA	Engineering Critical Assessment - another term for Defect Assessment.
Error	The difference between the measurement and the measurand is the error of the measurement. As the measurand is unknown it follows that the actual error is unknown.
Fitness-for-service	The ability to demonstrate the continued structural integrity of an in-service component containing a flaw until the next inspection point.
Height	Actual defect dimension in the approximate throughwall direction viewed in the elevation cross section of the component.
Indication	Signal from a discontinuity, such as a defect or a geometrical feature, of a type typical for the NDT method used.

Length	Defect length is the dimension of the defect along the main axis of a weld or a component as viewed in a plan or front elevation view.
Level	BS 7910 refers to three levels of defect assessment. Reference to assessment levels in this document refers to these BS 7910 levels (see next definition).
Level I Operator Level II Operator Level III Operator	BS EN 473:2000 “Non Destructive Testing . Qualification and certification of NDT personnel. General principles.” defines three levels of qualification of NDT operators. When level is used in conjunction with the operator or inspector, it is referring to these levels of qualification.
Ligament	The remaining material between a defect and the nearest surface of a component.
Maximum amplitude technique	Method of throughwall ultrasonic sizing by identifying the positions of the signals from the last facets of the defect nearest its extremities.
Measurand	The quantity being measured.
Probability of Detection	The likelihood of a defect being found in an application of a particular inspection technique. Usually given as a function of the size of the defect.
Random Errors	Errors which change from one measurement to the next and which can shift the measurement in either direction so that the mean error of a large number of measurements will be zero.
Standard Uncertainty	The standard deviation of the possible values of the measurement. If a measurand is not measured directly but derived from a series of other measurements, as is the case in NDT, then the uncertainty is estimated from combining the individual uncertainties of the separate measurements. Type A is the standard deviation derived from statistical analysis of a number of actual observations. Type B is an estimated value of standard deviation usually based on scientific judgment using all of the relevant information available.
Systematic Error	Errors which tend to shift all measurements in a systematic way so their mean value is displaced.
Through wall Extent	Defect dimension perpendicular to the nearest surface of the component.
Uncertainty	A parameter which characterises the spread of measurement values which could reasonably be expected from a particular value of the measurand given the errors of the measurement included.